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Characterization of return-stroke currents in rocket-triggered lightning

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[1] We present 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 the International Center for Lightning Research and Testing at Camp Blanding, Florida. The return-stroke current, after measurement, 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. Statistical information is presented for return-stroke peak current, charge transfer, half-peak width, and 10%–90% risetime. Our return-stroke peak current statistics are found to be generally consistent with those reported from other triggered-lightning studies and appear to be independent of electrical properties of the strike object, as previously found in another study. We 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. The means of the 10%–90% current risetimes for strikes to the power line (geometric mean 1.2 μs) and for strikes to the Earth (geometric mean 0.4 μs) are significantly different 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 in our direct and nearby-strike experiments.

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1. Introduction

[2] An accurate characterization of subsequent return-stroke currents in natural lightning is required for the design of adequate lightning protection. Lightning return-stroke currents in rocket-triggered lightning have similar, if not identical, properties to natural downward lightning subsequent stroke currents [e.g., *Fisher et al.*, 1993]. Consequently, the analysis of currents from rocket-triggered lightning is of considerable value.

[3] The experiments discussed in this paper were performed at the International Center for Lightning Research and Testing (ICLRT), an outdoor facility occupying about 1 km^2 at the Camp Blanding Army National Guard Base in north-central Florida. The ICLRT is located approximately midway between Gainesville, home of the University of Florida, and Jacksonville. At the ICLRT, lightning is triggered (artificially initiated) from natural overhead thunderclouds for a variety of purposes using the rocket-and-wire technique [e.g., *Uman et al.*, 1997; *Rakov*, 1999; *Rakov and Uman*, 2003]. Triggered lightning is typically composed of an initial stage involving an initial continuous current of the order of 100 A with a duration of hundreds of milliseconds followed by one or more dart leader-return-stroke sequences which are very similar, if not identical, to the strokes following the first stroke in natural lightning. An overview of the ICLRT is given in Figure 1 including a depiction of two test power lines–a distribution line with three vertically arranged phase conductors and a distribution line with three horizontally arranged phase conductors on which experiments were performed from 1999 through 2004. Both lines had a neutral conductor mounted beneath the phase conductors. Both direct lightning effects (lightning current

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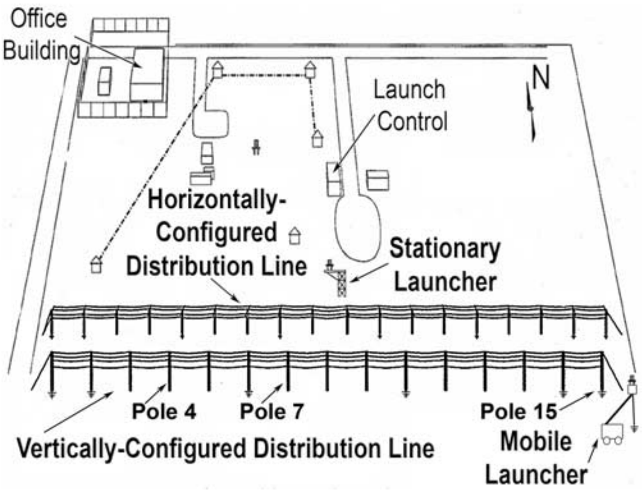

Figure 1. ICLRT overview, 2003. Lightning currents were triggered from the stationary launcher (1999 through 2004) and from the mobile launcher (2002 and 2003) positioned at five different locations—(1) 11 m southeast of pole 15 as shown in the figure, (2) 30 m north of pole 7, (3) 100 m north of pole 7, (4) 7 m south of pole 4, and (5) 15 m south of pole 4.

injected directly into a power line conductor [*Mata*, 2000, 2003; *Mata et al.*, 2003; *Schoene et al.*, 2007a, 2007b; *Schoene*, 2007]), and nearby lightning effects (lightning current injected into the Earth near the power line to investigate the voltages and currents induced in the power line conductors [*Paolone et al.*, 2004; *Schoene*, 2007]) were studied. Also shown in Figure 1 are the stationary-tower rocket-launching facility from which the triggered lightning current was directed to the power lines and the mobile launcher from which lightning was triggered for the nearby-lightning experiments.

[4] In this paper, the statistical parameters illustrated in Figure 2 are obtained for the lightning return-stroke currents measured during the 1999 through 2004 power line experiments. The characterization of the return-stroke current should be statistically representative because of the large sample size (206 return strokes) of the analyzed data. The quality of the direct-strike data was ensured by a thorough consistency check of the measured return-stroke current with the individual currents measured on the various phase-to-neutral connections and groundings of the power line [*Schoene et al.*, 2007a, 2007b].

2. Experiment Description

[5] From 1999 through 2004 lightning was triggered from a stationary launcher and its current was injected into the phase conductor (1999 through 2003) or neutral conductor (2004) of a horizontally-configured (1999 and 2000) or vertically-configured (2001 through 2004) test power distribution line. In this paper, these experiments are referred to as "direct-strike experiments". Both lines were over 800 m long and had three phase conductors and one neutral conductor. The line configurations varied between experiments but for most each phase conductor was connected to the neutral conductor through arresters located every 3 spans (horizontally-configured line) or every 4 spans (vertically configured line), and through 500 Ω terminators at both line ends. Also, for most line configurations the test line neutral was grounded at each arrester station and at the line terminations. Detailed information on the configuration of the direct-strike experiments can be found in the works of *Mata* [2000, 2003], *Mata et al.* [2003], *Schoene* [2007], and *Schoene et al.* [2007a, 2007b].

[6] Additionally, in 2002 and 2003 lightning was triggered from a mobile launcher and its current was injected into the Earth near the test power line to investigate induced effects on the line. The mobile launcher is a utility service vehicle with a rocket launcher installed in its "bucket". These experiments are referred to here as "nearby-strike experiments". Detailed information on the configuration of the nearby-strike experiments can be found in the works of *Paolone et al.* [2004], *Schoene et al.* [2007a, 2007b], and *Schoene* [2007].

[7] For both the direct and nearby-strike experiments, a Current Viewing Resistor (CVR) was mounted at the bottom of the launcher to measure directly the channel base current of the triggered lightning. The measured current signal was transmitted to the launch control trailer (Figure 1) via a Nicolet Isobe 3000 link (frequency response: DC to 15 MHz) composed of a receiver-transmitter pair and a connecting fiber optic cable where it was sampled with high-upper-frequency-response digital oscilloscopes (sampling rate between 10 MHz and 50 MHz) and low-upper-frequency-response digital oscilloscopes (sampling rate 1 MHz or 2 MHz). The high-upper-frequency-response oscilloscopes stored the data in a few millisecond long segments and the low-upper-frequency-response oscilloscopes sampled continuously for one or two seconds. The data were appropriately low-pass filtered to avoid aliasing. The measurement settings of the experiments are described

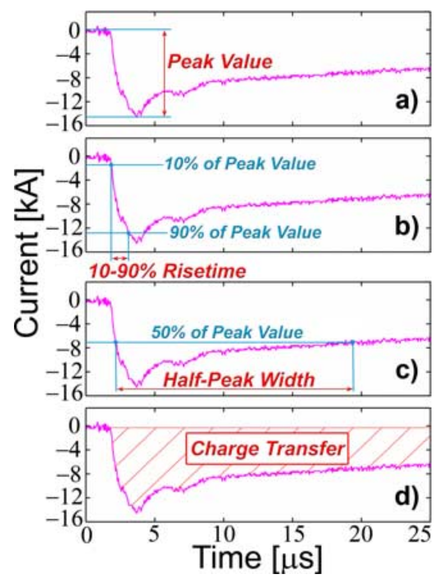

Figure 2. Typical triggered lightning return-stroke current waveform measured at the channel base (stroke FPL0315-2). The following return-stroke current parameters are illustrated: (a) peak value, (b) 10%–90% risetime, (c) half-peak width, and (d) charge transfer.

Table 1. Return-Stroke Current and Charge Statistics for the 1999 Through 2004 Experiments

					Horizontal Line		Vertical Line					Vertical Line With Overhead Ground Wire
		Total	Total, Direct	Total, Nearby	1999, Direct	2000, Direct	2001, Direct	2002, Direct	2002, Nearby	2003, Direct	2003, Nearby	2004, Direct
	Total number of flashes with return strokes	46	35	11	7	8	4	10	4	5	7	1
	Total number of flashes without return strokes	24	15	9	0	2	4	2	3	6	6	1
	Total number of recorded return strokes	206	169	37	26	37	14	64	16	26	21	2
Return-stroke current peak	Sample size	165	144	21	26	33	13	48	3	22	18	2
	Minimum (kA)	2.8	2.8	4.3	2.8	5.3	6.0	5.6	4.3	5.8	4.7	5.9
	Maximum (kA)	42.3	42.3	28.7	23.1	42.3	28.2	33.7	8.9	27.9	28.7	15.9
	Arithmetic mean (kA)	13.9	14.0	13.0	10.1	13.8	16.7	16.3	5.8	12.5	14.2	10.9
	Standard deviation (kA)	6.9	6.9	7.0	4.7	8.4	6.2	7.1	2.7	4.3	6.8	7.0
	Geometric mean (kA)	12.2	12.4	11.1	9.0	11.9	15.5	14.7	5.5	12.0	12.5	9.7
	Standard deviation, log	0.22	0.22	0.26	0.23	0.23	0.18	0.21	0.18	0.14	0.24	0.30
Return-stroke current 10%–90% risetime	Sample size	81	63	18	9	-	13	36	1	3	17	2
	Minimum (μs)	0.2	0.4	0.2	0.8	-	0.9	0.4	0.4	0.5	0.2	0.8
	Maximum (μs)	5.7	5.7	1.6	2.0	-	1.9	5.7	0.4	1.6	1.6	0.9
	Arithmetic mean (μs)	1.2	1.4	0.5	1.3	-	1.4	1.4	0.4	1.1	0.5	0.8
	Standard deviation (μs)	0.8	0.8	0.4	0.5	-	0.3	0.9	-	0.6	0.5	0.1
	Geometric mean (μs)	0.9	1.2	0.4	1.2	-	1.4	1.2	0.4	1.0	0.4	0.8
	Standard deviation, log	0.32	0.22	0.31	0.15	-	0.09	0.27	-	0.27	0.32	0.06
Return-stroke current half-peak width	Sample size	142	122	20	9	33	13	48	3	17	17	2
	Minimum (μs)	4	4	7	15	7	16	6	19	4	7	17
	Maximum (μs)	93	93	65	38	90	58	93	29	20	65	42
	Arithmetic mean (μs)	23	23	24	28	24	29	25	23	10	25	30
	Standard deviation (μs)	17	18	16	9	20	11	19	5	5	17	18
	Geometric mean (μs)	19	18	20	26	18	28	20	23	9	20	27
	Standard deviation, log	0.30	0.30	0.26	0.16	0.27	0.16	0.30	0.10	0.22	0.29	0.28
Return-stroke charge transfer within 1 ms	Sample size	151	122	29	9	33	13	48	11	17	18	2
	Minimum (C)	0.3	0.3	0.3	0.4	0.3	0.5	0.3	0.3	0.3	0.4	0.5
	Maximum (C)	8.3	8.3	2.7	2.5	8.3	7.3	4.1	1.1	6.0	2.7	2.1
	Arithmetic mean (C)	1.4	1.5	1.1	1.3	1.6	2.3	1.5	0.5	1.0	1.5	1.3
	Standard deviation (C)	1.4	1.4	0.8	0.8	1.9	1.8	1.0	0.2	1.3	0.8	1.1
	Geometric mean (C)	1.0	1.1	0.8	1.1	1.0	1.8	1.2	0.5	0.7	1.2	1.0
	Standard deviation, log	0.35	0.35	0.33	0.32	0.41	0.30	0.32	0.18	0.29	0.30	0.44

in detail in the works of *Mata* [2000], *Schoene et al.* [2007a, 2007b], and *Schoene* [2007].

3. Statistical Distributions of Return-Stroke Current Parameters

[8] In this section the experimental data collected on current wave shape characteristics are presented and compared with data from other studies of triggered lightning. As stated in the previous section, the validity of most of the analyzed data from our 2000, 2002, 2003, and 2004 direct-strike experiments has been checked by comparing the directly measured current at the launcher with the power-line phase-to-neutral currents and the currents flowing from the power line neutral to ground and/or by comparing measurements of the same return-stroke current by different systems [*Schoene*, 2007; *Schoene et al.*, 2007a, 2007b]. This consistency check showed that the return-stroke currents measured during the 2000 experiment [*Mata*, 2000] were probably overestimated by 25%. Consequently, an adjustment factor of 0.75 has been applied to these return-stroke current peaks and to corresponding charge transfers. Data which did not pass the consistency tests were excluded from the statistical analysis.

[9] Statistical information on the return-stroke current peak values, charge transfer within 1 ms, half-peak widths, and 10%–90% risetimes, including sample sizes, minimum/maximum values, arithmetic/geometric means, standard deviations, and logarithmic standard deviations (The logarithmic standard deviation of a parameter is found by calculating the standard deviation of the base-10 logarithm of this parameter.), is given in Table 1. The statistical information is listed separately for the direct and the nearby-strike experiments and for the combined data from all the power line experiments.

[10] Table 2 compare the statistical information presented here with statistics from experiments discussed by *Depasse* [1994], *Fisher et al.* [1993], *Crawford* [1998], *Rakov et al.* [1998], *Uman et al.* [2000], and *Schoene et al.* [2003]. Note

Table 2. Comparison of Return-Stroke Current and Charge Statistics Obtained From the 1999 Through 2004 Experiments at the ICLRT, With Results From Other Studies

		1999–2004 Direct-Strike Experiment	2002 and 2003 Nearby-Strike Experiment	1985–1991 Kennedy Space Center (KSC), Florida[a]	1986, 1990 and 1991 Saint-Privat d'Allier, France[a]	1990 Kennedy Space Center (KSC), Florida, 1991 Fort McClellan, Alabama[b]	1993 Camp Blanding, Florida[c]	1997 Camp Blanding, Florida[d]	1998 Camp Blanding, Florida[e]	1999 and 2000 Camp Blanding, Florida[f]
	Strike Object Information									
		Strikes to a Distribution Line Phase Conductor or Overhead Ground Wire	Strikes to an 8-m Long Vertical Grounded Wire.	R = 0.1–0.15 Ω	R = 9 Ω	KSC: R = 0.12 Ω[c]	R Initially Tens of Kiloohm[g]	R = 220 Ω	R = 58 Ω or 350 Ω	Strikes to a 70 × 70 m Buried Metal Grid (R = 6 Ω)
Return-stroke current peak	Sample size	144	21	305	54	45	37	11	25	64
	Minimum (kA)	2.8	4.3	2.5	4.5	<2.0	5.3	5.3	5.9	5.0
	Maximum (kA)	42.3	28.7	60.0	49.9	38.0	44.4	22.6	33.2	36.8
	Arithmetic mean (kA)	14.0	13.0	14.3	11.0	-	15.1	12.8	14.8	16.2
	Standard deviation (kA)	6.9	7.0	9.0	5.6	-	-	5.6	7.0	7.6
	Geometric mean (kA)	12.4	11.1	-	-	12.0	13.3	11.7	13.5	14.5
	Standard deviation, log	0.22	0.26	-	-	0.28	0.23	0.20	0.19	0.21
Return-stroke current 10%–90% Risetime	Sample size	63	18	-	37	43	-	11	-	63
	Maximum (μs)	5.7	1.6	-	4.9	2.9	-	4.0	-	2.4
	Arithmetic mean (μs)	1.4	0.5	-	1.1	-	-	0.9	-	0.3
	Standard deviation (μs)	0.8	0.4	-	1.1	-	-	1.2	-	0.4
	Standard deviation, log	0.22	0.31	-	-	0.29	-	0.39	-	0.44
	Minimum (μs)	4	7	-	15	-	-	7	-	2
	Maximum (μs)	93	65	-	103	-	-	100	-	37
	Arithmetic mean (μs)	23	24	-	50	-	-	36	-	13
	Standard deviation (μs)	18	16	-	22	-	-	25	-	9
	Geometric mean (μs)	18	20	-	-	18	-	29	-	11
	Standard deviation, log	0.30	0.26	-	-	0.30	-	0.29	-	0.32
Return-stroke charge transfer within 1 ms	Sample size	122	29	-	-	-	-	-	-	-
	Minimum (C)	0.3	0.3	-	-	-	-	-	-	-
	Maximum (C)	8.3	2.7	-	-	-	-	-	-	-
	Arithmetic mean (C)	1.5	1.1	-	-	-	-	-	-	-
	Standard deviation (C)	1.4	0.8	-	-	-	-	-	-	-
	Geometric mean (C)	1.1	0.8	-	-	-	-	-	-	-
	Standard deviation, log	0.35	0.33	-	-	-	-	-	-	-

[a]*Depasse* [1994].
[b]*Fisher et al.* [1993].
[c]*Rakov et al.* [1998].
[d]*Crawford* [1998].
[e]*Uman et al.* [2000].
[f]*Schoene et al.* [2003].
[g]Grounding resistance initially very high but probably lowered considerably once lightning connected to one of three coaxial cables buried 1 m beneath ground surface.

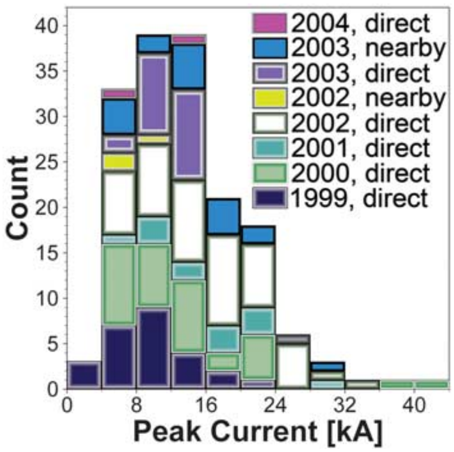

Figure 3. Histogram of return-stroke current peaks. An adjustment factor of 0.75 has been applied to the current peaks from the 2000 experiment.

that Schoene et al. presented data that were collected during 1999 and 2000 at the ICLRT at Camp Blanding, but those data are from an experiment different from the 1999 and 2000 power line experiments presented here (Schoene et al. triggered lightning with an underground launcher and injected the lightning current into a buried metallic ground plane). The direct and nearby-strike experiments in Tables 1 and 2 are considered separately to reveal any potential influence of the strike objects (power-line conductor or Earth grounding electrode) on the analyzed parameter. Where available for a specific experiment, Table 2 contains information on the strike object and its measured low-frequency, low-current grounding resistance. Histograms of the return-stroke current peak, charge transfer within 1 ms, half-peak widths, and 10%–90% risetime are presented in the following sections where the statistical information listed in Tables 1 and 2 is also discussed.

3.1. Return-Stroke Current Peaks

[11] The statistical information listed in Tables 1 and 2 and the histogram in Figure 3 show that the geometric mean and standard deviation of the 144 return-stroke peak currents measured during the direct-strike experiment (geometric mean: 12.4 kA, logarithmic standard deviation: 0.22) are very similar to the mean and standard deviation of the 21 peak currents from the nearby-strike experiments (geometric mean: 11.1 kA, logarithmic standard deviation: 0.26) and appear to follow a similar log-normal distribution. The corresponding arithmetic mean values and standard deviations are also similar for the direct-strike experiment (arithmetic mean: 14.0 kA, standard deviation: 6.9 kA) and the nearby-strike experiment (arithmetic mean: 13.0 kA, standard deviation: 7.0 kA). These results are consistent with peak current statistics from the 1985–1991 Kennedy Space Center experiments [*Depasse*, 1994], the 1993 Camp Blanding experiment [*Rakov et al.*, 1998], and the 1997 Camp Blanding experiment, as seen in Table 2: the peak currents from these three experiment have arithmetic means that are within 10% of the peak current means of both the direct and nearby-strike experiments. The arithmetic mean of the peak currents from the 1986, 1990 and 1991 Saint-Privat d'Allier experiment, 11 kA for 54 peaks [*Depasse*, 1994] is 3 kA and 2 kA smaller than the means for the direct and nearby-strike experiments, respectively. The arithmetic mean of the peak currents from the 1998 Camp Blanding experiment, 14.8 kA for 25 peaks [*Crawford*, 1998] is 0.8 kA and 1.8 kA larger than the means for the direct and nearby-strike experiments, respectively. The arithmetic mean of the peak currents from the 1999 and 2000 Camp Blanding experiments, 16.2 kA for 64 peaks [*Schoene et al.*, 2003], is 2.2 kA and 1.2 kA larger than the means for the direct and nearby-strike experiments, respectively. The current peaks measured during the 1999 and 2000 Camp Blanding experiment have the largest mean values of all the experiments compared, which might in part be attributable to the relatively high trigger threshold (5 kA) used in the 1999 Camp Blanding experiment causing a bias toward events with larger return-stroke peak currents (the triggering threshold for the 2000 Camp Blanding experiment was lowered to 3.2 kA). *Depasse* [1994] and *Fisher et al.* [1993] report that at least 5% of their triggered lightning current peaks were below 5 kA. Note that for some events return-stroke currents from segmented records (triggering threshold present) were not available. For these events, return-stroke currents from full-flash records (no triggering threshold) were analyzed, if available, thereby reducing the bias toward larger mean values due to triggering threshold. The dependence of peak current on a lower measurement limit (trigger level) were studied by *Rakov* [1985], the dependence on grounding conditions by *Depasse* [1994], the dependence on trigger threshold level, strike object geometry, and on grounding conditions by *Rakov et al.* [1998], and the dependence on strike-object height by *Rakov* [2001]. Depasse hypothesized a dependence of peak current on grounding resistance, based on a comparison between the data collected in 1985 to 1991 at the KSC (grounding resistance values 0.1–0.15 Ω) and the data collected in 1986 to 1991 at Saint-Privat d'Allier, France (grounding resistance of 9 Ω). Rakov et al. could not find such a dependence using various data sets obtained at the KSC, Fort McClellan, and Camp Blanding, where the grounding resistance ranged from 0.1 Ω to more than hundreds of ohms. *Schoene et al.* [2003] observed a tendency for larger current peaks to be associated with better grounding from the comparison of Camp Blanding measurements (In the comparison of different Camp Blanding experiments, any variations due to different storm types and local topography are likely minimized relative to comparisons of results from completely different geographical locations.) in different years, although the year-to-year variation of return-stroke peak currents from experiments with the same grounding conditions (the 1999 and 2000 Camp Blanding experiments) appears to be more significant than the variation for peak currents obtained under different grounding conditions.

3.2. Return-Stroke Charge Transfer

[12] The charge transfer was obtained by numerically integrating the measured return-stroke current over 1-ms time intervals. Tables 1 and 2 show that the arithmetic mean and standard deviation of the 122 charge transfers measured during the direct-strike experiment (geometric mean: 1.1 C, logarithmic standard deviation: 0.35) are both larger than the ones for the 29 charge transfers from the nearby-strike experiments (geometric mean: 0.8 C, logarithmic standard

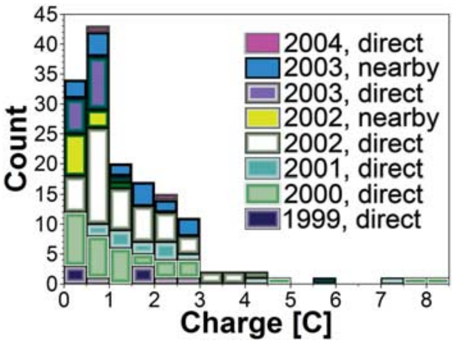

Figure 4. Histogram of return-stroke charge transfers within 1 ms. An adjustment factor of 0.75 has been applied to the charge from the 2000 experiment.

deviation: 0.33). The histogram in Figure 4 shows that none of the 29 charge transfers from the nearby-strike experiment is larger than 3 C, while 11 of the 122 charge transfers from the direct-strike experiment are larger than 3 C and 3 charge transfers are larger than 7 C. The absence of large charge transfers during the nearby-strike experiment is reflected in the smaller mean values and standard deviations and might be attributable to statistical variation because of the relatively small number of return strokes triggered during the nearby-strike experiment. The combined statistical distribution of the charge transfers from the two experiments shown in Figure 4 resembles a log-normal distribution.

[13] The return stroke neutralizes the charge deposited by the leader and consequently the return-stroke charge per unit length and the leader charge per unit length are expected to be similar. The charge deposited by stepped leaders that precede first return strokes in natural lightning is an important parameter for understanding the attachment process and hence in the design of lightning protection. If the charge distribution along the leader channel is known, it can be used to calculate the electric field between the leader tip and objects on the ground thus determining the striking distance (The striking distance is the distance between the descending leader tip and the to-be-struck object at the time it is essentially certain that the object will be struck. This time is when an upward-directed leader emerges from the object that initiates a return stroke when it connects to the downward-directed leader. The striking distance is important, for example, in the design of power line protection [e.g., *Rakov and Uman*, 2003].) [*Cooray et al.*, 2006; *Uman*, 2008]. However, very little statistical data on charge deposited by leaders preceding first strokes are available, which motivates the investigation of the correlation between leader charge and return-stroke current peak, since the statistical distribution of return-stroke current peaks is reasonably well known, and hence the leader charge can be estimated if such a correlation exists. *Berger* [1972] and *Berger et al.* [1975] analyzed 89 first return-stroke current peaks from natural lightning and the corresponding charge transferred to ground during the first millisecond, or so, of the return-stroke current waveform and found a weak correlation between the current peak and charge transfer (R^2 = 0.59, where R^2 is the coefficient of determination). The current peaks and charge transferred within 1 ms of 143 rocket-triggered lightning return strokes based on our rocket-triggered lightning experiments are shown in Figure 5 on a log-log scale. They are better correlated (R^2 = 0.76) than in the Berger 1-ms data. The regression equation, $y = 10.6x^{0.7}$, given by *Uman* [1987] for the first return-stroke data of Berger, is also plotted in Figure 5 for comparison. The power regression equation for the rocket-triggered lightning data is $y = 12.3x^{0.54}$. Additional comparison of the correlation of return-stroke current peaks and charge transfers based on our rocket-triggered lightning data and Berger's natural lightning data will be the subject of a future paper.

3.3. Return-Stroke Current 10%–90% Risetime

[14] The histogram of the 10%–90% risetimes of the return-stroke currents shown in Figure 6a exhibits two distinct peaks–one in the 0.2 to 0.4 μs range and the other in the 1.2 to 1.6 μs range. Separating the data into two histograms, one for all risetimes from the direct-strike experiments (Figure 6b) and another for all risetimes from the nearby-strike experiments (Figure 6c), reveals that the statistical distributions of the risetimes for the direct and nearby-strike experiment are different: the arithmetic mean of 1.4 μs for the current risetimes based on the direct-strike experiment is significantly larger than the arithmetic mean of 0.5 μs for the current risetimes based on the nearby-strike experiment. The distribution of the current risetimes from the former experiments resembles a normal distribution, while the distribution of the current risetimes from the latter experiments may resemble a log-normal distribution, although the sample size of 18 for the nearby-strike experiment is insufficient to confidently identify the distribution type.

[15] The principal difference between the direct and nearby-strike experiments that possibly accounts for the different risetime distributions is the strike object–a metallic object (rocket launcher or intercepting structure) connected to a distribution line conductor for the former

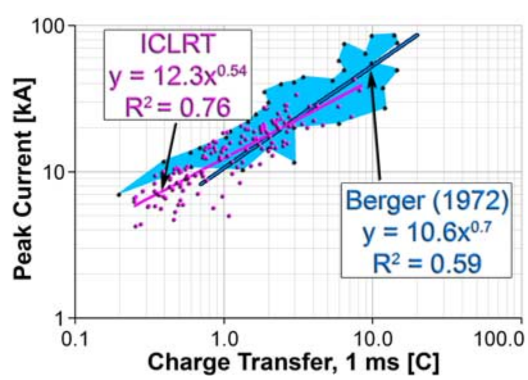

Figure 5. Current peaks as a function of charge transfer within 1 ms for 143 rocket-triggered lightning return strokes triggered at the ICLRT from 1999 through 2004. The regression power equation and R^2 value are given. The regression line for 89 negative first return strokes in natural lightning found by Berger is also displayed. The shaded area represents an envelope that encompasses all Berger data points (only the outside values that confine the shaded area are shown).

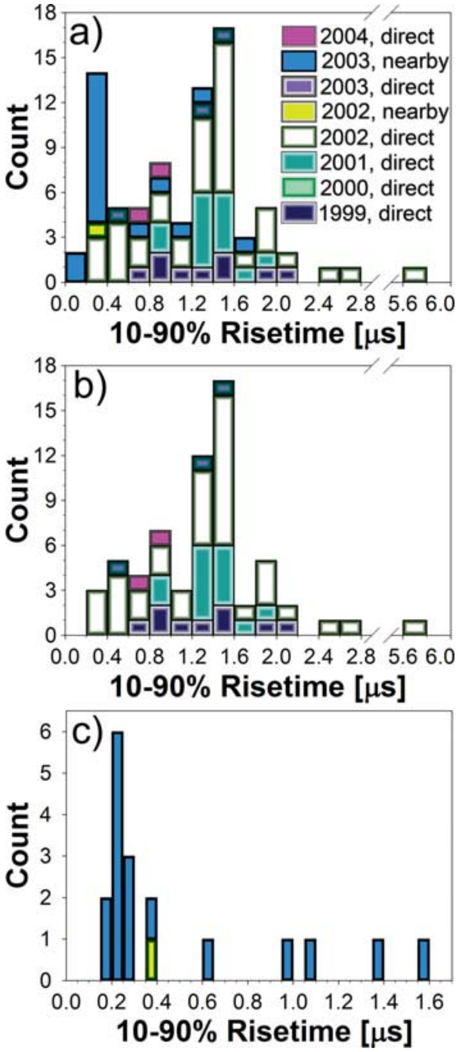

Figure 6. Histograms of return stroke current 10%–90% risetimes. (a) Direct and nearby strikes, (b) only direct strikes, and (c) only nearby strikes. The horizontal scale in Figures 6a and 6b is interrupted between 2.8 and 5.6 μs. The vertical and horizontal scales in Figure 6c are different from the scales in Figures 6a and 6b.

experiment and an elevated, directly (via a relatively short down conductor) grounded launcher for the latter experiment (see "Experiment Description" section). The larger risetimes in the direct-strike experiment can likely be attributed to the larger characteristic (surge) impedance of the struck line conductor (compared to the lumped impedance of a short downconductor in the nearby-strike experiment), to reflections of the lightning current at impedance discontinuities such as the line arrester and the line grounds, or to a combination of both effects. Note that for the 2004 experiment, we injected the lightning current into the grounded neutral conductor of the power line, which electrically may more resemble the nearby-experiment strike object, since both strike objects were directly connected to ground as opposed to the struck-phase conductors in the 1999 through 2003 direct-strike experiments, which were connected to ground through the arresters and line terminators.

[16] A comparison (see Table 2) of the arithmetic/geometric means of the 10%–90% risetimes from the direct-strike experiment (1.4 μs/1.2 μs) with the means from four other experiments shows that the means from the other experiments were smaller. On the other hand, the arithmetic/geometric mean of the 10%–90% risetimes from the nearby-strike experiment (0.5 μs/0.4 μs) is among the lowest means in Tables 1 and 2; only the arithmetic/geometric mean from 1999 and 2000 Camp Blanding experiment reported by *Schoene et al.* [2003] is slightly lower (0.3 μs/0.2 μs) and that experiment involved triggered strikes to a very good grounding electrode, an underground launcher connected to a 70 m × 70 m buried metallic ground plane.

3.4. Return-Stroke Current Half-Peak Width

[17] The statistical information listed in Tables 1 and 2 and the histogram in Figure 7 show that the geometric mean and standard deviation of the 122 half-peak widths of the return-stroke currents measured during the direct-strike experiment (geometric mean: 18 μs, logarithmic standard deviation: 0.3) are very similar to the geometric mean and standard deviation of the 20 half-peak widths from the nearby-strike experiments (geometric mean: 20 μs, logarithmic standard deviation: 0.26) and identical to the geometric mean and standard deviation of the 45 half-peak widths in the works of *Fisher et al.* [1993] (mean: 18 μs, standard deviation: 0.3 μs). These similarities suggest that the half-peak width of the channel base current does not depend on the properties of the strike object (as opposed to an apparent dependency of the 10%–90% risetimes on the properties of the strike object discussed in the previous section). On the other hand, Tables 1 and 2 show that the arithmetic means of the direct and nearby-strike experiments (23 μs and 24 μs, respectively) are significantly smaller than the 50 μs mean of 54 half-peak widths from the Saint-Privat d'Allier experiment [*Depasse*, 1994] and the 36 μs mean of 11 half-peak widths from the 1997 Camp Blanding experiment [*Crawford*, 1998] and significantly larger than the 13 μs mean of 64 half-peak widths from the 1999 and 2000 Camp Blanding experiment involving the buried ground plane [*Schoene et al.*, 2003]. It is not clear why the half-peak width means are different for different experiments (some of which were conducted at the same geographical location as the experiment presented here). Although our data did not show a dependency between the half-peak width and the properties

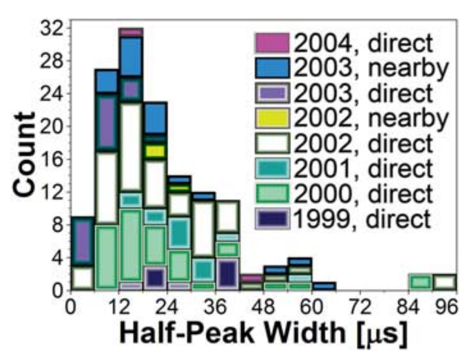

Figure 7. Histogram of return-stroke current half-peak widths.

of the strike object, we cannot rule out the possibility that such a dependency exists and the strike objects in the other experiments may have affected the half-peak widths of the stroke currents measured in these experiments. Generally, strike objects with smaller low-current, low-frequency grounding resistances appear to result in smaller half-peak widths. For instance, the lowest mean, 13 μs, was found in the 1999 and 2000 Camp Blanding experiment where the ground electrode was a 70 m by 70 m buried metallic ground plane.

[18] It is also worth noting that half-peak width measurements are sensitive to both high- and low-frequency errors. The influence on high-frequency errors on the half-peak width is discussed by *Fisher et al.* [1993], who point out that an insufficient high-frequency response can result in an overestimation of the half-peak width. (An insufficient high-frequency response typically results in underestimated peak and half-peak. This results in an overestimation of the half-peak width since the width of the waveform at half-peak value is determined closer to the bottom, where the waveform is wider.) Low-frequency errors due to an insufficient low-frequency response of the measurement system will affect the tail of the lightning current waveform in such a way that the current decays faster. This will result in an underestimation of the half-peak width. Half-peak width statistics published in the literature should be viewed critically because of these potential problems. Measurement errors due to insufficient upper and lower frequency responses of the measuring system may be responsible for some variation between our half-peak width statistics and statistics found in the literature. We feel confident about the accuracy of our data since the frequency response of our measurement system was DC to at least 10 MHz, which is sufficient for determining the half-peak width and, as mentioned before, we performed a consistency check on most of our lightning-channel-base current data with currents measured at other points in the system. Nonetheless, one subset of our half-peak width data is an outlier: the 17 half-peak widths of the currents measured during the 2003 direct-strike experiment have a significantly lower geometric mean (9 μs) than the means of the other subsets (between 18 μs and 28 μs). The reason for the discrepancy is not clear, but it may be related to the fact that 13 of the 17 events were from the same flash (FPL0312), a flash with an unusually large number of strokes (a total of 16 strokes of which 3 strokes did not pass the consistency check and were not included in the statistical analysis). The largest half-peak widths during the 2003 direct-strike experiment were from a two-stroke flash (16 μs and 20 μs) and from a one-stroke flash (17 μs). Perhaps there is a tendency of (1) half-peak widths of strokes from the same flash to be similar and/or (2) return-stroke currents from flashes with a large number of strokes to have smaller half-peak widths — either tendency would explain the low half-peak width mean in our 2003 direct-strike experiment. The first hypothesis, for which there is some support found in the literature (see next paragraph), would result in a statistical error because of small sample size since the 13 return strokes from the same flash can be viewed as representing more or less one event and the sample size of the 2003 subset would in effect be five (and not 17). The second hypothesis is speculative and difficult to prove or disprove because of the limited number of available data from flashes with large number of return strokes.

[19] *Fisher et al.* [1993] who compared triggered lightning current data from different experiments noted that "there is a remarkable similarity between the different return-stroke current waveforms within a given triggered lightning flash". Fisher et al. also point out that *Berger* [1967] made a similar observation for subsequent strokes in natural lightning. Our observed similarity of the half-peak widths of the 13 currents from flash FPL0312 supports Fisher et al.'s finding. It is worth noting that the geometric mean of the charge transfer for the 13 strokes was also unusually low (0.6 C) compared to the geometric mean of all strokes in our data (1.0 C). In contrast, the geometric mean of the current peak values for the 13 strokes (11.3 kA) was similar to the geometric mean of all strokes in our data (12.2 kA). Risetimes were not available for the 13 strokes.

4. Summary

[20] A statistical analysis of over 200 lightning return-stroke currents measured during the power line experiments conducted from 1999 through 2004 at the ICLRT has been presented in this paper. The statistical data have been compared to corresponding results of other rocket-triggered lightning studies. The results of this comparison can be summarized as follows:

[21] 1. The statistical distribution of return-stroke peak currents found in this study is generally consistent with those based on other studies. In particular, the arithmetic mean of the return-stroke current peaks found here (14.0 kA for 144 events) is very similar to the arithmetic mean found in the study with the largest sample size, the arithmetic mean of the peak values of 305 currents measured at the Kennedy Space Center from 1985 to 1991, 14.3 kA [*Depasse*, 1994]. Discrepancies between the return-stroke peak current statistics presented here and in other publication may be attributable to (1) differences in sample size (2) differences in the trigger threshold, and/or (3) instrumental and methodological errors in the other studies. A dependency of the return-stroke current peak on the electrical properties of the strike object was not observed in the present study. This is consistent with the finding of *Rakov et al.* [1998] that the average return-stroke peak current in triggered lightning is not much influenced by either strike-object geometry or level of man-made grounding, ranging from excellent to none.

[22] 2. The statistical distribution of the 10%–90% risetimes of return-stroke currents directly injected into a power line is different from the distribution of the 10%–90% risetimes of return-stroke currents injected into a grounding electrode of the launcher (nearby-strike experiment). The generally larger risetimes observed during the direct-strike experiment are apparently due to the relatively large characteristic impedance of the struck line conductor and/or reflections of the lightning current at impedance discontinuities on the line such as the line arresters and line grounds. A comparison of the arithmetic/geometric means of the 10%–90% risetimes from the direct-strike experiment with the means from four other experiments shows that the means from the other experiments were smaller. The arithmetic/geometric mean of the 10%–90% risetimes from the

nearby-strike experiment is among the lowest means, and comparable to the mean for current injection into a buried 70 m × 70 m ground plane.

[23] 3. A dependence of the return-stroke current half-peak width on the electrical properties of the strike object was not observed for our direct and nearby-strike experiments. However, it cannot be ruled out that such a dependency exists, based on a comparison with other studies that employed different strike objects and found half-peak widths with mean values that were very different from the half-peak width mean value in our study.

[24] 4. We analyzed 13 stroke currents in the 16-stroke flash FPL0312 and found that the currents exhibited similar half-peak widths. This supports Fisher et al's finding that stroke currents in the same flash have a tendency to have similar waveshapes.

[25] The relation between return-stroke current peaks and charge transfer within 1 ms has been investigated. The results can be summarized as follows:

[26] The relation of 143 rocket-triggered lightning return-stroke current peaks and the corresponding charge transfer within 1 ms after return-stroke initiation are related by a power law equation ($y = 12.3x^{0.54}$, where y is the peak current and x is the charge transfer, $R^2 = 0.76$, where R^2 is the coefficient of determination). *Berger et al.* [1975] found a weaker correlation ($R^2 = 0.59$) between 89 first lightning return-stroke current peaks and corresponding 1-ms charge transfers. The regression equation from Berger et al.'s first return-stroke data is $y = 10.6x^{0.7}$. Additional comparison of the correlation of return-stroke current peaks and charge transfers in our rocket-triggered lightning data and Berger's natural lightning data will be the subject of a future paper.

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