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High-speed video observations of positive lightning flashes to ground

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[1] Although positive lightning flashes to ground are not as frequent as negative flashes, their large amplitudes and destructive characteristics make understanding their parameters an important issue. This study summarizes the characteristics of 103 positive cloud-to-ground (+CG) flashes that have been recorded using high-speed video cameras (up to 11,800 frames per second) in three countries together with time-correlated data provided by lightning location systems (LLS). A large fraction of the +CG flashes (81%) produced just a single stroke, and the average multiplicity was 1.2 strokes per flash. All the subsequent strokes in multiple-stroke +CG flashes created a new ground termination except one. The geometric mean of 21 interstroke time intervals was 94 ms, which is about 1.5 times larger than the average interstroke interval in negative CG flashes (~60 ms); 75% of the +CG flashes contained at least one long continuing current (LCC) ≥ 40 ms, and this percentage is significantly larger than in the negative flashes that produce LCCs (approximately 30%). The median estimated peak current (I_p) for 116 positive strokes that created new ground terminations was 39.4 kA. Positive strokes with a large I_p were usually followed by a LCC, and both of these parameters are threats in lightning protection. The characteristics presented here include the multiplicities of strokes and ground contacts, the percentage of single-stroke flashes, the average interstroke time interval, the durations of the continuing current, and the distributions of I_p, the total flash durations, and the 2-D leader speeds.

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1. Introduction

[2] Although positive cloud-to-ground (+CG) lightning flashes are usually not as frequent as negative flashes, their special characteristics of high peak current, large impulse charge, and long continuing current make understanding their physical parameters an important issue. The largest directly measured peak currents and charge transfers to ground are produced by +CG flashes [*Berger et al.*, 1975]. Positive flashes are also a major concern for the designers of lightning locating systems because their electromagnetic waveforms are frequently very large and often have a complex structure [*Cummins*, 2000].

[3] The first comprehensive statistical data on the characteristics of positive CG flashes were presented by *Berger et al.* [1975] who measured the currents in 26 positive discharges that struck a tall tower in Lugano (Switzerland). Although more then 30 years have passed since those measurements were conducted, and Berger himself was not sure whether those flashes were initiated by upward or downward propagating leaders [*Berger*, 1977, p. 146], those data are still used in practically all the engineering standards for lightning protection.

[4] Beginning in the 1980s, positive lightning has been studied using electric field measurements in conjunction with video recordings. *Rust et al.* [1981] measured the field risetimes, the durations of the continuing current, and the total durations of 31 positive flashes. *Fuquay* [1982] measured the durations of the continuing current (CC) in 75 positive flashes that were recorded in 48 thunderstorms. *Beasley et al.* [1983] reported data for three flashes that were unambiguously identified as positive discharges, and *Ishii et al.* [1998] used multiple-station electric field measurements to determine the locations of the strike points in 14 multiple-stroke +CG flashes, the number of different strike points, and the horizontal distances between those strike points.

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[5] More recently, *Fleenor et al.* [2009] have analyzed 204 +CG flashes that were recorded in the Central Great Plains using standard video cameras (60 fields per second) in conjunction with data provided by the U.S. National Lightning Detection Network (NLDN) and electric field measurements. Fleenor et al. found that the average multiplicity of positive flashes was only 1.04 strokes per flash and that the interstroke intervals in nine multiple-stroke positive flashes had a mean of 50 ms. These authors were also the first to document clear evidence that the subsequent strokes in multiple-stroke +CG flashes can follow the same channel as the first stroke.

[6] More recently, the development of high-speed CCD video cameras and GPS timing techniques have allowed the luminous properties of lightning to be recorded with very high time resolution [*Saba et al.*, 2006a, 2006b, 2008, 2009; *Campos et al.*, 2007, 2009; *Campos and Saba*, 2009; *Saraiva et al.*, 2010]. With high-speed cameras, almost all of the subsequent strokes that remain in the same channel can be resolved in time, and the detailed geometrical development of the leaders, branches, and other processes can be recorded with relative ease.

[7] *Mazur et al.* [1998] used a high-speed video camera operating at 1000 frames per second and a VHF radio interferometer to record the propagation of spider lightning channels that were associated with two positive CG flashes. Several years later, *Saba et al.* [2006b], using high-speed video recordings of nine +CG flashes, confirmed that such flashes tend to have a high peak current followed by a long continuing current, and both of these parameters are threats in lightning protection.

[8] In 2008, *Kong et al.* [2008] described the characteristics of one downward propagating positive leader. *Saba et al.* [2008] also gave statistics on the two-dimensional (2-D) speeds of positive leaders and showed that, contrary to what was usually assumed, the average downward speed of a positive leader is not significantly different from the average downward speed of a negative leader. Saba et al. also documented that positive leaders often produce very short duration recoil leaders (RLs) during their development and that the RLs have a highly branched structure that is not usually recorded by conventional video cameras or on photographs.

[9] More recently, *Saba et al.* [2009] have documented that +CG flashes can be initiated by intracloud discharges of either polarity, a behavior that may help us understand why extensive intracloud discharges often precede +CG flashes. The association of extensive intracloud lightning with +CG flashes implies that the field changes from positive discharges cannot always be modeled as the neutralization of a simple, vertically stacked charge models [*Rakov*, 2003]. Moreover, this complex structure of +CG flashes is related to and may explain the morphology of certain types of sprites in the middle atmosphere [*Mika and Haldoupis*, 2008; *Asano et al.*, 2009; *Campos and Saba*, 2009; *Lang et al.*, 2010] and why sprites tend to be more common above large-area thunderstorm complexes [*Lyons et al.*, 2008].

[10] *Campos et al.* [2009] and *Campos and Saba* [2009] have used high-speed video recordings to measure the properties of M components during the CC phase of +CG flashes and given statistics on the continuing current wave shapes. These authors have also speculated about how the M components and CC wave shapes will contribute to the production of transient luminous events in the middle atmosphere that are often observed to be associated with +CG flashes (for other related papers on the subject, see *Yashunin et al.* [2007], *Cummer* [2003], and *Asano et al.* [2009]).

[11] Although positive discharges have received more attention in recent years, our knowledge about the physical parameters of positive lightning still lags that for negative lightning and many questions remain. This paper will summarize the combined results of our observations of +CG lightning flashes that were recorded using high-speed video cameras in correlation with data from lightning locating systems in Austria, Brazil, and the United States. Our main object will be to provide an up-to-date summary of the physical parameters of positive CG lightning. Given the small data sets in some locations, we could not verify if any regional differences were present in the parameters analyzed (as done by *Saraiva et al.* [2010] for negative CG flashes). However, the Brazilian data set, which was the largest one, was presented separately in some figures and tables.

2. Instrumentation

2.1. High-Speed Cameras

[12] Six different high-speed digital video cameras (Photron Fastcam 512 PCI, Red Lake Motion Scope 8000S, Phantom v7.1, v310, v12.1 and Basler Pilot piA640–210gm), with time resolutions and exposure times ranging from 83 microseconds (11,800 frames per second) to 10 ms (100 frames per second), have been used to record images of cloud-to-ground lightning in southern and southeastern Brazil, southern Arizona, South Dakota, and Vienna (Austria) between February 2003 and September 2009. All video imagery was recorded without any frame-to-frame persistence and was time-stamped to GPS. The minimum recording length of all the cameras was two seconds; previously, *Saraiva et al.* [2010], in a multiple-camera study, reported a maximum flash duration of 1.4 s with approximately 99% of the more than 400 cases lasting less than 1 s for negative CG flashes. We believe that this recording length is sufficient also for positive lightning, as discussed in the following sections. For more details about the accuracy of high-speed camera technology for lightning observations and more details on the measuring systems, see the works by *Saba et al.* [2006a], *Warner and Orville* [2009], and *Schulz and Saba* [2009].

2.2. Lightning Location Systems

[13] All recordings were obtained in geographical regions that were covered by Vaisala lightning location systems (BrasilDat in Brazil, the NLDN in the United States, and ALDIS in Austria). These systems are nearly identical, and further information about their performance can be found in the work of *Schulz et al.* [2005], *Cummins and Murphy* [2009], and *Naccarato and Pinto* [2009]. Data from the lightning location systems (LLS) were used to obtain the stroke polarity, an estimate of the peak current (I_p) in each stroke, and the locations of the ground strike points. The polarity identification was also double-checked in approximately 40% of the data set with the help of electric field measurements; no contradiction was observed in the analyzed data set.

Table 1. Summary of the Positive Cloud-to-Ground Flashes in our Data Set

Country	Location	Latitude/Longitude	Thunderstorm Days	Number of Flashes	Frame Rates (frames per second)
Austria	Vienna	48.1400°N/16.1258°E	1	9	100 and 200
Brazil	S. José dos Campos	23.2125°S/45.8670°W	13	35	1000 and 4000
	S. Martinho	29.4439°S/53.8230°W	6	34	1000 and 4000
	Uruguaiana	29.7587°S/57.0721°W	1	1	1000
United States	Tucson	32.2144°N/110.9181°W	6	9	1000 and 4000
	Rapid City	44.0468°N/102.8291°W	8	15	11800
Total			35	103	100 to 11,800

2.3. Electric Field Measurement System

[14] The electric field measuring system consisted of a flat plate antenna with an integrator/amplifier, a GPS receiver, and a PC with two PCI cards (a GPS card Meinberg GPS168PCI and a data acquisition card NI PCI-6110), and a data acquisition box (DAQ BOX NI BNC-2110). The waveform recording system was configured to operate at a sampling rate of 5 MS/s on each channel and the resolution of the A/D converter is 12 bits. The same type of measuring system has been used previously in lightning experiments in Austria and Sweden and is described in more detail by W. Schulz et al. (LLS data and correlated continuous E-field measurements, paper presented at VIII International Symposium on Lightning Protection (SIPDA), Inst. of Electrotech. and Energy, São Paulo, Brazil, 2005).

3. Data and Methodology

[15] For the purposes of this paper, we have assembled a database of events in different countries/regions where positive flashes are rare compared to negative flashes. A total of 103 positive cloud-to-ground discharges that were initiated by downward propagating leaders were recorded at the locations listed in Table 1. Owing to the fact that the data collected in Brazil is a significant amount of the whole data set (70 out of the 103 +CG flashes), their results for some parameters were presented separately. The total number of strokes in the 103 flashes was 124. Apart from the fact that positive flashes are not as frequent as negative flashes, the low number of positive events in Table 1 is likely due to the fact that the cameras were usually pointed in directions that had high flashing rates, and high flashing rates usually come from the regions of storms or cells that produce negative flashes.

[16] Information about the time, location, amplitude, and polarity of each stroke was obtained from the LLS that was operating in each country. If the stroke locations were not reported by the LLS, the polarity information was determined using the raw LLS sensor data and/or the electric field measurements. Flashes were considered to have a positive polarity if all strokes in the flash had positive polarity, and the few flashes that contained strokes with both polarities were not included in the data set. Individual strokes were grouped into flashes based on analyses of the video recordings, LLS data, and the electric field measurements when available (40% of the positive flashes had their electric field signature recorded). All flashes occurred at ranges of 1 km to 60 km from the camera sites. A total of nine (out of 124) strokes listed in this work were completely out of the camera field of view.

[17] For some of the parameters described here, we used measurements from all 103 +CG flashes; however, for parameters that required better observational conditions, only a subset of the data set was used (e.g., for the duration of a CC, the visibility must be such that at least part of the lightning channel above ground was recorded on video).

4. Results

4.1. Multiplicity

[18] Figure 1 shows a histogram of the number of strokes per flash for all 103 +CG flashes in our data set. In this sample, 19 flashes had two strokes and one had three strokes. The distribution for the Brazilian data set (70 +CG flashes) is also shown in Figure 1. Although there are some prior reports of positive CG flashes having more than two strokes (e.g., *Heidler and Hopf* [1998], based on electric field measurements of 45 +CG flashes in Germany), there are no prior video recordings of positive flashes with more than two strokes.

[19] The average number of positive strokes per flash for both data sets in Figure 1 is 1.2. The percentages of single-stroke flashes are approximately 80%, a value that is consistent with the 75% reported by *Heidler and Hopf* [1998] based on electric field measurements.

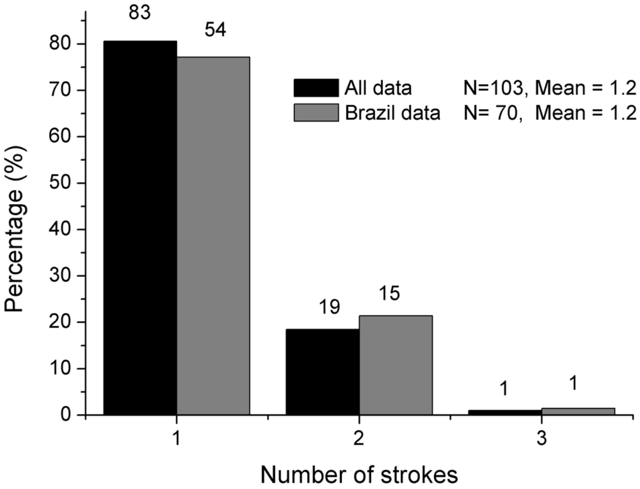

Figure 1. Number of positive flashes that contained the given number of strokes.

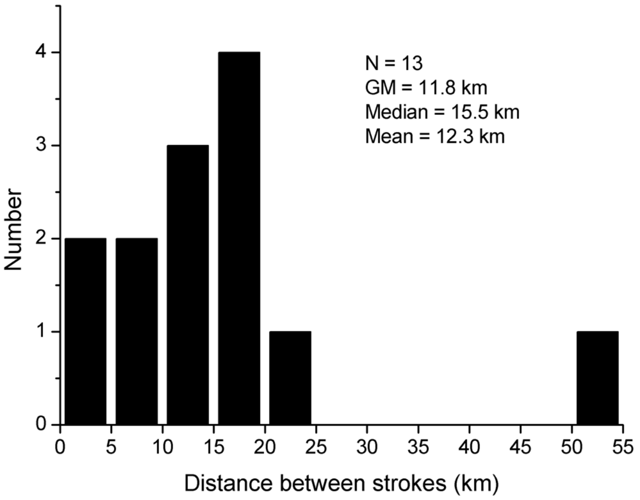

Figure 2. Histogram of the horizontal distances between the different ground contacts in multiple-stroke +CG flashes.

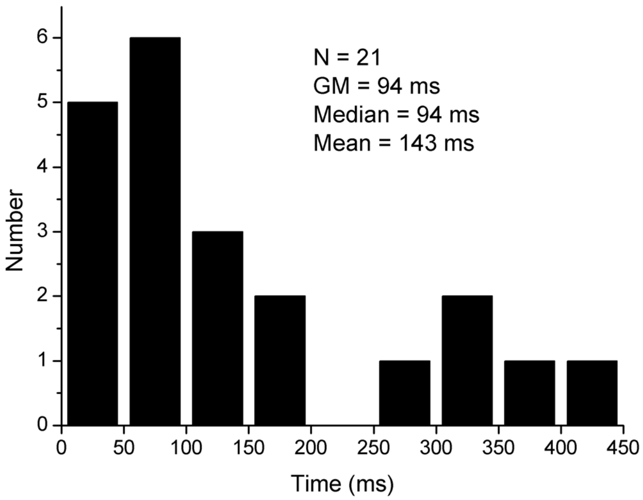

Figure 3. Distribution of 21 interstroke intervals in 20 multiple-stroke +CG flashes.

4.2. Number of Ground Strike Points

[20] It was possible to see the locations of the ground strike points in 98 of the 103 flashes in our data set. The total number of different strike points was 111; therefore the average number of strike points per flash was 1.14. There are no prior reports of this parameter in the literature. It is important to note that all but one subsequent stroke in the 20 multiple-stroke positive flashes in our data set created a new ground termination.

[21] For the multiple-stroke positive flashes where each stroke was located by an LLS, we were able to estimate the horizontal distances between the different ground strike points, and these are plotted in Figure 2. Note that the distances in Figure 2 range from 2 to 53 km and that most (70%) are greater than 10 km, the default range used by the LLSs to group strokes into flashes [*Cummins and Murphy*, 2009]. We did not present a separate histogram for Brazil because only one case (out of 13) was not observed there. For the 22 and 59 negative flashes that were analyzed by *Thottappillil et al.* [1992] and *Stall et al.* [2009], respectively, all distances between the different ground strike points were found to be less than 10 km.

4.3. Interstroke Intervals

[22] To the best of our knowledge, there are only three prior reports of the interstroke time intervals in multiple-stroke +CG flashes: *Cooray and Perez* [1994] in Sweden, *Heidler and Hopf* [1998] in Germany, and *Fleenor et al.* [2009] in the United States. Figure 3 shows the distribution of our measurements, and Table 2 compares our values with those reported by other investigators. The arithmetic mean (AM) and geometric mean (GM) of 21 time intervals between strokes in the 20 multiple-stroke +CG flashes in our data set are 143 ms and 94 ms, respectively. The smallest and the largest intervals in Figure 3 are 14 ms and 406 ms, respectively.

[23] Because +CG flashes rarely produce more than one stroke, the numbers of interstroke intervals in Table 2 are small; nevertheless, the combined studies (with the exception of *Fleenor et al.* [2009]) show that the GM interval in +CG flashes is about 1.5 times larger than the corresponding interval in negative flashes [*Saba et al.*, 2006a; *Rakov and Uman*, 2003].

4.4. Estimated Peak Current

[24] Figure 4 shows the distribution of the estimated peak currents (I_p) for the 116 +CG strokes (out of 124 for the whole data set) and for the 79 +CG strokes (out of 87 for the Brazilian data set) that were recorded using high-speed cameras and were reported by an LLS. Note that the values of I_p provided by an LLS have never been validated by direct measurement for positive first or subsequent strokes and that the field-to-current conversion factors that the LLSs uses for positive strokes are the same as for negative strokes.

[25] The median value of I_p for the 116 positive strokes (whole data set) in Figure 3 was 39.4 kA, and the smallest and largest values were 4.8 kA and 142 kA, respectively. Note that the low I_p values are for real CG strokes recorded on video and are not contaminated by LLS reports of cloud discharges. Twenty one percent of the positive strokes recorded on video had an I_p that was less than 20 kA, nearly half of which were subsequent strokes. A similar result was found for the Brazilian data set.

[26] Table 3 shows statistics of the I_p values for first and subsequent positive strokes (for the whole data set and also for Brazil separately) together with the values obtained by *Fleenor et al.* [2009]. Here, we only compare our data with Fleenor et al. because those authors also used LLS data

Table 2. Summary of Interstroke Time Intervals in Cloud-to-Ground Flashes

	N	GM (ms)	AM (ms)	SD (ms)
This work	21	94	143	125
United States [*Fleenor et al.*, 2009]	9	27	50	54
Germany [*Heidler and Hopf*, 1998]	16	101	120	97
Sweden [*Cooray and Perez*, 1994]	29	92	64	-

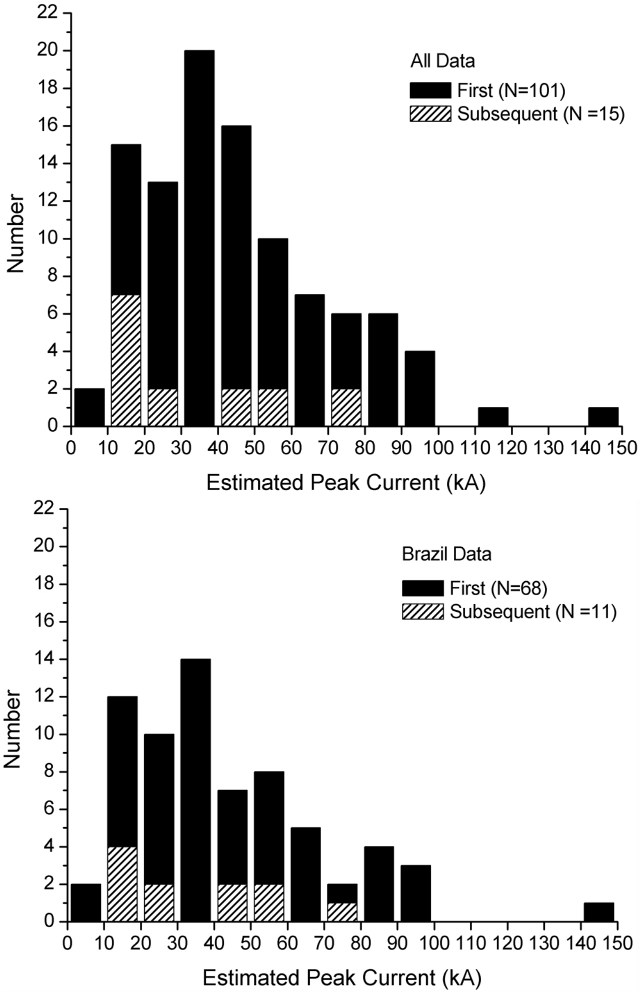

Figure 4. Histogram of the estimated peak currents for the whole data set and for the Brazilian data set.

(from the NLDN) to determine values of I_p. The sample sizes of the positive subsequent strokes in Table 3 are small, so for those events, the mean and median values should be viewed with caution.

[27] Note in Table 3 that positive first strokes have mean and median values of I_p that are about two times larger than the negative first strokes reported by *Fleenor et al.* [2009]. The values for positive subsequent strokes are also larger than for negative subsequent strokes (see Table 3). There was only one positive subsequent stroke in our data set that remained in a preexisting channel, and it had an I_p of 11kA.

4.5. Continuing Current

[28] The continuing current is a continuous mode of charge transfer to the ground following the initial peak, and the large charge transfers in positive flashes can be attributed to the longer and higher values of CC compared to negative single-stroke flashes [*Rakov and Uman*, 2003]. Three categories of CC have been defined in previous studies of positive flashes. *Kitagawa et al.* [1962] and *Brook et al.* [1962] defined "long" CC as one that had a duration longer than 40 ms, as indicated by a slow increase in the electric field with time. *Shindo and Uman* [1989] defined a "short" CC as one with a duration between 10 ms and 40 ms, and a "questionable" CC as one lasting 1 to 10 ms. On the basis of recordings obtained with high-speed video cameras, *Ballarotti et al.* [2005] introduced the term "very short" continuing currents to describe CCs with a duration less than or equal to 10 ms but greater than 3 ms in order to avoid contamination from what might be just a long tail on the return stroke current impulse.

[29] Here, we have measured the durations of CC by visual inspection of the longest-lasting luminous segment in the channel above ground. For these measurements, the brightness of the channel was enhanced as needed by changing the image settings of the video player software. Although different cameras were used to record the stroke luminosity at variable distances, and with varying sky backgrounds, all cameras appeared to record faint CCs provided that the events were not too far from the recording site. In order to avoid significant variations due to the sensitivity of the individual cameras, only flashes that were less than 50 km from the recording sites were examined. (Note that positive events that exhibited CCs in Austria were not analyzed because of the lower time resolution of that camera.)

[30] Only two positive flashes out of the 87 in our data set did not produce any CC, and at least one long CC event (>40 ms) was present in 75% of the flashes. The categories of CC for 104 positive strokes are shown in Figure 5. Sixty seven (64%) of these 104 positive strokes were followed by a long CC. The shortest and the longest CCs had a duration of 5 ms and 800 ms, respectively. Figure 6 shows the distribution of the CC durations in 104 positive first and

Table 3. Comparison of the Estimated Peak Currents of First and Subsequent Strokes in Cloud-to-Ground Flashes

			Number	Mean (kA)	SD (kA)	Median (kA)	GM (kA)
First	positive	All data	101	44.8	26.1	40.0	37.4
		Brazil	68	42.3	26.8	35.0	34.4
		Fleenor et al. [2009]	204	48.8	24.2	44.8	
	negative	*Fleenor et al.* [2009]	91	23.3	13.6	19.6	
Subsequent	positive	All data	15	32.9	22.1	27.0	26.4
		Brazil	11	34.5	20.7	28.3	28.8
		Fleenor et al. [2009]	9	36.1	19.9	26.6	
Subsequent NGC[a]	positive	All data	14	34.4	22.0	27.7	28.2
		Brazil	11	34.5	20.7	28.3	28.8
	negative	*Fleenor et al.* [2009]	50	19.4	8.6	17.8	

[a] NGC stands for new ground contact.

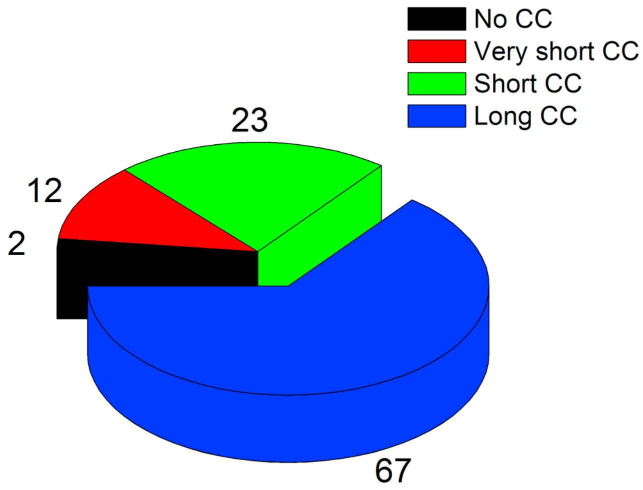

Figure 5. Number of positive strokes that had various categories of CC (in this categorization, long CC have durations longer than 40 ms, short CC have duration between 10 ms and 40 ms, and very short CC between 3 and 10 ms).

subsequent strokes. The arithmetic mean and the geometric mean durations are 149 ms and 74 ms, respectively.

[31] Figure 7 shows a plot of I_p versus the duration of CC for the 70 positive strokes in our data set that produced a long CC. Note that Figure 7 corroborates a prior finding of *Saba et al.* [2006b] based on a smaller sample of only nine +CG strokes; namely, positive strokes can produce both a high peak current (I_p > 20 kA) and a long CC (>40 ms), a feature that has not been found in any negative stroke. (Figure 7 includes a plot of 586 newly analyzed negative strokes for comparison, including cases followed by long CC.) Note also in Figure 7 that the stroke with the largest estimated peak current (142 kA) was followed by the longest CC (800 ms), and this event is marked by an arrow in the upper right corner of the plot.

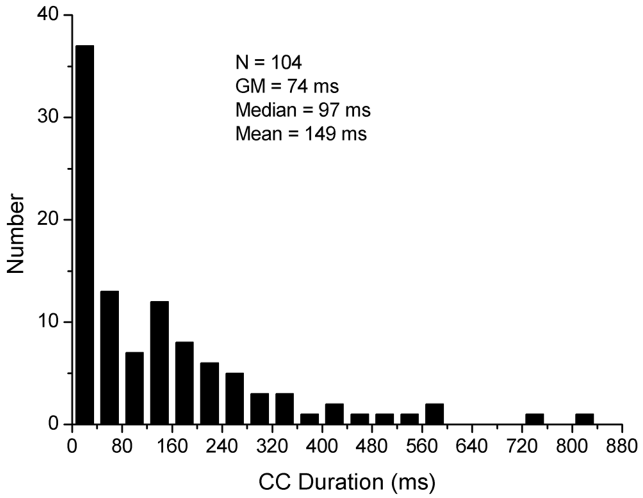

Figure 6. Histogram of the CC durations in 104 positive strokes.

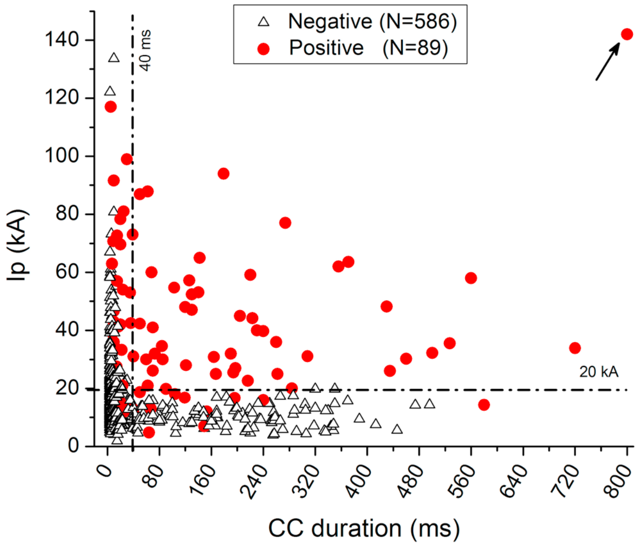

Figure 7. Scatterplot of the estimated peak current (I_p) versus CC duration.

4.6. Flash Duration

[32] For this study, we have defined the total duration of a flash as the time between the occurrence of the first return stroke and the end of the continuing current following the last stroke, if present. If the flash contains only one stroke, then its total duration is the same as the duration of the CC that follows the stroke. Single stroke positive flashes that did not have a CC have been excluded from this analysis.

[33] Figure 8 shows a histogram of the total durations of 85 positive flashes in our data set. Here, the geometric and arithmetic means are 125 ms and 204 ms, respectively. The maximum duration (912 ms) was observed for a flash that produced three strokes, and the last stroke was followed by a CC that lasted 165 ms. Although most positive flashes

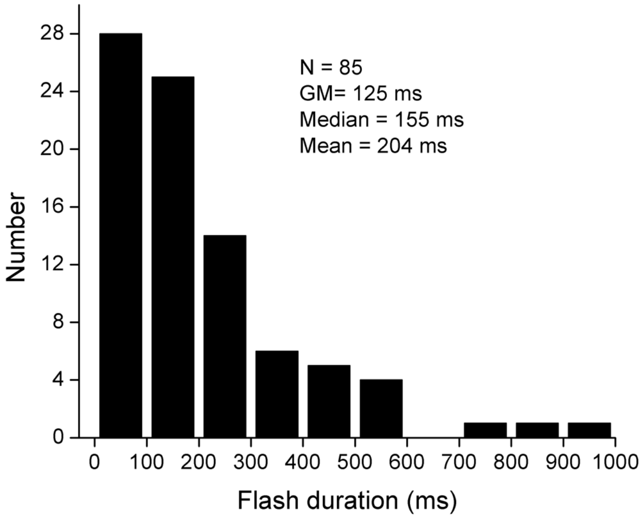

Figure 8. Histogram of the total durations of positive CG flashes.

Table 4. Summary of Positive Leader Speeds[a]

	Sample Size	Min	Max	Mean	Median	GM
Partial	449	0.08	16.2	-	-	-
Average	29	0.24	11.8	2.76	1.80	1.81

[a] Two-dimensional speeds (×10^5 m/s). Min stands for minimum, Max stands for maximum, and GM stands for geometric mean.

produce just a single stroke, the median duration of positive flashes (155 ms) is similar to average duration of negative flashes (163 ms for 233 negative flashes, as reported by *Saba et al.* [2006b]). This similarity is likely because 74% of the single-stroke positive flashes are followed by long CC and because the interstroke intervals in multiple-stroke positive flashes are larger.

4.7. Leader Speeds

[34] The framing rates available in the high-speed cameras used in this study were fast enough to resolve the 2-D downward speeds of propagation of the positive leaders that preceded some of the +CG flashes that were recorded. A total of 29 cases showed a visible leader propagating toward ground and were considered in this study. This data set has been partially presented previously (nine cases) by *Saba et al.* [2008], who have also defined the terminology that we will use here: “speeds measured along the path of the leader” are termed “partial speeds,” and the “average speed” is calculated by dividing the length of the entire 2-D trajectory by the time taken to cover it [*Saba et al.*, 2008, p. 2]. For the 29 cases that were analyzed, a summary of the results is shown in Table 4. As only 11 cases (out of the 29) were recorded in Brazil, their results were not presented separately. Both the distributions of 29 average speeds and also 449 partial speeds follow a lognormal distribution at the 0.05 level, according to a test developed by *Shapiro and Wilk* [1965]. Owing to the large number of partial speeds that were measured on some of the slowest leaders, we did not compute the overall mean in these cases because they would be biased toward lower values. It was possible to measure two or more partial speeds in 28 out of the 29 leaders that were analyzed, and this has allowed us to determine how the average 2-D speed changes as a positive leader propagates toward ground. When each case was examined separately (as in the work of *Saba et al.* [2008]), 82% of the positive leaders accelerated as they approached the ground, 7% decelerated, and 11% oscillated around an average speed.

5. Summary

[35] We have measured several important characteristics of positive CG flashes using high-speed video cameras in conjunction with time-correlated LLS data. To the best of our knowledge, these are the first such measurements of a wide number of parameters to be reported using this technique.

[36] The majority (81%) of the +CG flashes recorded in three countries were single-stroke flashes. The average multiplicity was 1.2 positive strokes per flash, and all but one subsequent stroke in the multiple-stroke positive flashes created a new ground termination. The geometric mean interstroke interval in multiple-stroke +CG flashes was 94 ms. This value is almost 50% larger than the geometric mean interstroke interval in negative flashes [*Saba et al.*, 2006a; *Rakov and Uman*, 2003]. In our discussion of Table 2, we noted that most other studies report positive interstroke intervals that are similar to our value. An exception is the value reported by *Fleenor et al.* [2009], probably because they found a larger fraction of subsequent strokes remaining in the same channel (four out of nine subsequent strokes) and the intervals in these cases were less than 40 ms. The only subsequent stroke that remained in a preexisting channel in our data set also had an interstroke interval that was less than 40 ms (15 ms). Although a few of the subsequent strokes that created new ground contacts had interstroke intervals less than 40 ms (three out of 21), most occurred after an interval that was longer than 40 ms (18 out of 21).

[37] Most (75%) of the horizontal distances between different ground contacts in the flashes that exhibited multiple ground terminations are larger than 10 km. This is likely because most positive CG flashes develop in the presence of extensive horizontal channels in the cloud.

[38] Positive first strokes have mean and median values of I_p that are about two times larger than the negative first strokes, and are similar to the positive first strokes reported by *Fleenor et al.* [2009]. The values for positive subsequent strokes are also larger than for negative subsequent strokes (see Table 3).

[39] The distribution of the durations of the continuing current in +CG flashes (see Figure 6) is based on high-speed video measurements. Only two positive flashes out of the 87 in our data set did not produce any CC, and at least one long CC event (>40 ms) was present in 75% of the flashes. This is in marked contrast to the low percentage (30%) of negative flashes that contain a long CC [*Rakov and Uman*, 1990; *Correia and Saba*, 2008]. We have corroborated the observations of *Saba et al.* [2006b] that the positive strokes followed by long CC do not show any dependence on the estimated peak current of the preceding stroke, by using significantly more cases than were analyzed by those authors. The stroke that had the largest estimated peak current (142 kA) also produced the longest CC (800 ms). This supports the common observation that positive CG flashes produce the largest charge transfers to ground.

[40] Another observation is that some +CG strokes produce a new ground contact while there is still a CC from a previous stroke flowing to ground (two cases out of 21). This is extremely rare in negative flashes (only one or two cases in more than 2000 flashes recorded to date). This may be occurring because +CG flashes are commonly associated with extensive horizontal channel development. In fact, *Kong et al.* [2008] and *Saba et al.* [2009] have observed positive downward leaders being initiated by the CC phase of intracloud discharges. The facts that (1) almost all the subsequent strokes in multiple-stroke +CG flashes create a new ground termination, (2) positive strokes are frequently associated with flashes that exhibit extensive horizontal channel development, (3) subsequent strokes can make a new ground contact even during the continuing current of the previous stroke, and (4) the large distances between the different ground contacts in +CG flashes, all indicate a very low interdependence of positive strokes on each other. This leads us to conclude that the temporal and spatial criteria

that are commonly used in lightning locating systems to group negative strokes into flashes may not be valid for +CG flashes. This use of the same grouping criteria may also contribute to the low positive stroke multiplicities that are often reported by LLSs [e.g., *Orville and Huffines*, 2001]. The very concept of a lightning "flash" being a group of strokes that are colocated in space (and time) should be reconsidered for positive flashes to ground.

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