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Negative cloud-to-ground lightning properties from high-speed video observations

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[1] From analysis of digital high-speed video records of 233 negative cloud-to-ground (CG) lightning flashes associated with 27 thunderstorms in southeastern Brazil, various lightning properties have been determined. The analysis of the video records showed that although 20% of them were single-stroke flashes and the average number of strokes per flash was 3.8, a significant variation was observed in these parameters from storm to storm. In a smaller subset containing 138 flashes, 70 (51%) had multiple terminations on the ground. As 138 flashes produced 235 different strike points, the average number of strike points per CG flash was 1.70. Considering that in this study the missing of strokes is practically negligible, we can say from the average multiplicity and from the average number of strike points per flash that each ground contact point is, on average, struck 2.2 times. The 608 time intervals between strokes of 186 negative multiple-stroke flashes presented a geometric mean value of 61 ms. Although time intervals preceding subsequent strokes that create a new termination tend to be greater than intervals between subsequent strokes that follow the previously formed channel, the difference was not statistically significant. A strong positive correlation between the number of subsequent strokes in a flash and the flash minimum duration may indicate that some processes concerning the time requisite for the channel decay and for the positive leader in the cloud to provide more charges for the next stroke do not permit multiple strokes to occur under a certain minimum time duration.

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1. Introduction and Review

[2] The studies by *Winn et al.* [1973] and *Brantley et al.* [1975] are among the first that used standard video tape recordings to analyze the characteristics of cloud-to-ground (CG) lightning flashes. *Winn et al.* [1973] measured the frequency of occurrence and time interval between different channels to ground in a given CG flash. *Brantley et al.* [1975] extended the previous work to include statistical data on the time duration of CG flashes, on the number of strokes per ground flash, and on the time intervals between all strokes in a flash and between only those strokes having spatially separate channels. More recently, *Valine and Krider* [2002] presented statistics and characteristics on CG flashes with multiple ground contacts based also in VHS tape records.

[3] Biases that are introduced by finite video resolution of standard video tape recordings have been discussed by *Winn et al.* [1973], *Brantley et al.* [1975], *Thomson et al.* [1984], *Rakov and Uman* [1990], *Idone et al.* [1998], *Valine and Krider* [2002], and *Rakov and Huffines* [2003]. If two different strokes occur within the 33 ms interval they will appear to be a single stroke. According to *Thomson et al.* [1984], this is the time duration of the uncertainty window of standard video images even if odds and evens fields of the frames are analyzed separately. Two strokes along the same channel separated by a short interval might fail to be individually distinguished if they occur within one field or if they appear in adjacent fields. In the latter case, without substantially increased luminosity evident in the video record, the second field image would be interpreted as continuing current following the earlier stroke [*Idone et al.*, 1998].

[4] On the other hand similar studies that use only electric field change records may confuse K changes with return strokes unless there is sufficient bandwidth to positively identify return strokes [*Thomson et al.*, 1984; *Miranda et al.*, 2003; *Rakov and Huffines*, 2003].

[5] In order to avoid such biases, some studies use simultaneous video and electric field observations trying to combine the best features of each method to identify strokes [e.g., *Parker and Krider*, 2003; *Thomson et al.*, 1984; *Rakov and Uman*, 1990; *Kitagawa et al.*, 1962].

[6] The advent of high-speed motion CCD video cameras allowed the use of temporal high-resolution video images of lightning flashes. With these cameras, the missing of strokes that occur at relatively short time intervals is practically excluded. This new technique has been used in the analysis of some isolated events [e.g., *Mazur et al.*, 1995, 1998;

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Saba et al., 2004]. In the past, rotating film camera was used in some studies to resolve strokes separated in time as little as 30 μs [e.g., *Schonland*, 1956; *Kitagawa et al.*, 1962].

[7] In this paper we present, to the reach of our knowledge, the first study on statistics and characteristics of a large number of CG flashes using a high-speed motion camera. During the summers of 2003 and 2004, 264 CG flashes were recorded with this camera. The flashes occurred in the Paraíba Valley region, a valley that nearly covers the extension from São Paulo to Rio de Janeiro (southeast Brazil), during 27 days of thunderstorm activity. Most of our results are compared to other studies that have an accurate stroke counting according to *Rakov and Huffines* [2003].

2. Data Collection Techniques

[8] The observing sites used during the data acquisition are located at São José dos Campos (23.212°S; 45.867°W, altitude: 635 m) and at Cachoeira Paulista (22.686°S; 44.984°W; altitude: 625 m). These observational sites have nearly 360° field of view. It is possible to visualize distant thunderstorms occurring within a radius of 80 km from the sites. Both sites are located in a region that is well covered by the Brazilian lightning locating system, RINDAT (Figure 1).

[9] Video recordings were made simultaneously with a Red Lake 8000S Motion Scope high-speed camera and a commercial Sony digital CCD camera. The Red Lake 8000S Motion Scope is capable to record sequences of images from 60 to 8000 frames per second, depending on the setting. Images from the camera or from the image memory are displayed on the computer monitor. Each sequence of images can be stored in a computer file, retrieved and replayed at various speeds to analyze a motion sequence in detail.

[10] The Motion Scope system has a trigger system that detects a signal from an external source and stops the recording at the frame active at the receipt of the trigger. We can set the trigger point to determine how many frames we record before the event. Each trigger pulse was initiated manually, depressing a handheld switch when a flash occurs. All high-speed video recordings had a 1 s pretrigger time and a total recording time of 2 s. The frame rate used was 1000 frames per second with the aim of visualizing most of the phases of CG lightning: stepped leaders, return strokes, and continuing currents.

[11] The video frames of the high-speed camera were GPS time stamped to an accuracy of 1 ms. This synchronization allowed the correlation of each flash recorded with the ones detected by the lightning locating system. Detection efficiency of the network in the region was near 90% for flashes and near 50% for strokes [*Ballarotti*, 2005]. Contrary to most of similar studies that used event-to-thunder time intervals to find the distances to flashes, this study identified most of the distances using the solutions given by the network. It was also possible to read the polarity and other parameters in the solutions.

[12] The commercial Sony DC-TRV330 Digital 8 video camera was used so that a broader field of view could be observed. By comparing images from both cameras we were able to practically discard the possibility of missing strokes of multichannel flashes that could have occurred out of the field of view of the high-speed camera.

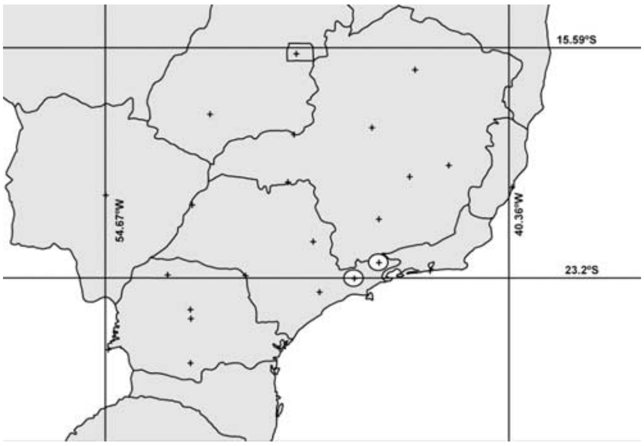

Figure 1. Map indicating the location of lightning sensors of the Brazilian lightning location system at the time of the observations [*Pinto*, 2003]. Circles indicate the location of the observing sites.

3. Analysis and Results

[13] Out of 264 CG flashes, 233 had their polarity identified as negative CG flashes. The information about the polarity of each individual stroke was determined by the lightning detection network. This information is available even if the location of the stroke is not computed by the system. Flashes are considered to have negative polarity if all detected strokes have negative polarity. All flashes occurred at distances of 1 to 80 km from the site.

[14] For some parameters described in the following sections, we used all 233 negative CG flashes in the statistics. For some parameters in section 3.3 that required a better image quality of the stroke channels, a subset of 138 negative CG flashes was used.

3.1. Flash Multiplicity

[15] In order to calculate the average number of strokes per flash (multiplicity), a special care was taken with two situations that could reduce the accuracy of stroke counting (1) multiple channel flashes occurring too close and out of view of the camera and (2) strokes with channels obscured by rain. In the first case, channels occurring outside the field of the view of the camera would be lost; in the second case, CG strokes could be mistaken by an intracloud stroke. Most of these relatively difficult cases were solved using the wide-angle standard video camera or using data from the lightning detection network.

[16] Figure 2 shows a histogram for the number of strokes per flash in 233 flashes. Of these 233 flashes, 186 had two or more strokes. The number of flashes containing two strokes is greater than containing only one (single-stroke flashes); and the average number of strokes per flash is 3.8.

[17] The percentage of single-stroke flashes is 20%. This value is fairly similar to other accurate stroke counting studies confirming that, when the possibility of missing strokes is practically excluded, the overwhelming majority (about 80% or more) of negative CG flashes contains more

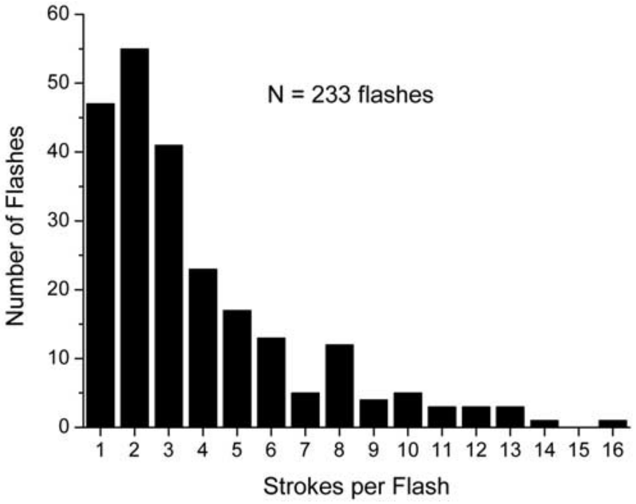

Figure 2. Number of flashes that contained the given number of strokes. The total number of strokes was 890, and the average number of strokes per flash was 3.8.

than one stroke [*Rakov and Huffines*, 2003]. Some other results from these "accurate stroke count" studies are summarized in Table 1. Note that the average number of strokes per flash was also relatively similar to other studies.

[18] Table 2 shows these variations for a subset of thunderstorm days with significant amount of data. Note that there is a significant variation in the percentage of single-stroke flashes and in the average multiplicity from day to day. Although, the reason why that happens is out of the scope of this study, we would like to emphasize that, as recommended by *Rakov and Huffines* [2003], in order to minimize any bias, data should be collected from as many thunderstorms as possible. Observations of only 2 or 3 thunderstorms may give average values that are not representative of a given region.

3.2. Flash Duration

[19] Flash duration is here defined as the time interval between the occurrence of the first return stroke and the end of the continuing current following the last return stroke, if present. The median duration of the 233 flashes was 163 ms. Although measured by different techniques, similar median durations of 180 ms and 175 ms were obtained by *Berger et al.* [1975] and *Diendorfer et al.* [1998], respectively. The maximum duration value (1356 ms) was observed in a flash that produced 16 strokes. This flash had also the maximum number of strokes per flash. Figure 3 shows the duration distribution.

[20] A scatterplot illustrating the relation between flash duration and the number of strokes per flash is shown in Figure 4. It is possible to observe a clear threshold establishing a minimum value of duration for a given number of strokes per flash. Figure 5 shows a strong positive correlation between the number of subsequent strokes in a flash and the flash minimum duration seen in Figure 4. Note that the strokes in these flashes have not necessarily used the same channel and that only one flash does not follow this tendency. The regression line slope gives the average minimum interstroke interval (72 ms). Note that it is lower than the interstroke interval arithmetic mean value obtained for all strokes together (83 ms, see section 3.4).

[21] The strong correlation shown in Figure 5 seems to indicate that processes in the channel and in the cloud do not permit multiple strokes occur under a certain minimum duration; if an interstroke interval is very short, others will have to be large, so that on average there will be a minimum duration. Two possible reasons could explain such behavior: (1) there is a minimum time requisite for the channel from the previous stroke to decay to the point appropriate to support the propagation of the next stroke dart leader [see, e.g., *Uman and Voshall*, 1968] and (2) there is a maximum rate of charge supply for the occurrence of the next stroke. Following the bidirectional leader concept described by *Mazur* [2002], this second hypothesis could reveal that there is an average minimum time required for the positive leader in the cloud to provide more charges for the following stroke occur once the previous channel has already decayed. Both hypotheses complement each other and may explain the flash duration lower limit for a certain multiplicity.

3.3. Multigrounded Lightning Flashes

[22] Seventy flashes (51%) showed spatially separate ground strike points in a subset of 138 flashes, for which the number of ground contact points could be clearly identified (flashes with channels obscured by precipitation, terrain or too diffuse were discarded). This value is very similar to the 50% found by *Rakov et al.* [1994] in Florida and to 49% found by *Kitagawa et al.* [1962] in New Mexico. If only multiple-stroke flashes of this subset are considered (104 flashes), this percentage grows to 68%.

3.3.1. Number of Strike Points

[23] Figure 6 shows how the number of ground strike points was distributed among the subset of 138 flashes. A total of 235 strike points gives an average of 1.70 strike points per CG flash. This means that the average number of lightning strike points is 70% higher than the number of flashes. This percentage is very similar to the 67% or, 1.67 strike points per CG flash, found in Florida [*Rakov et al.*, 1994] and higher than the 45% value found by *Valine and Krider* [2002] in Arizona for positive and negative flashes. The presence of positive flashes, which have lower multiplicity, certainly diminished the overall average number of strike points reported by *Valine and Krider* [2002].

[24] Considering that in this study the missing of strokes is practically negligible, we can say from the average multiplicity (3.8) and from the average number of strike points per flash (1.7), that each ground contact point is, on average, struck 2.2 times. Knowledge of this parameter, as of the relative occurrence of single- and multiple-stroke is useful in estimating the probability of successful circuit breaker reclosure following a lightning-caused outage of the power line [*Anderson and Eriksson*, 1980; *Rakov and Huffines*, 2003].

3.3.2. Effect of Stroke Order

[25] It was observed a rapid decrease with stroke order in the percentage of subsequent leaders that create a path to ground different from that of the previous stroke. The percentages of the second and third leaders that create a new channel are very similar to those found in Florida (Figure 7). The major differences appear in the percentage of the fourth leader: 12% in this study. The percentage of

Table 1. Number of Strokes per Negative Flash (Multiplicity) and Percentage of Single-Stroke Flashes From Accurate Stroke Count Studies

Study	Location and Latitude	Number and Type of Storms	Total Number of Flashes	Maximum Multiplicity	Percent of Single-Stroke Flashes	Average Multiplicity
Kitagawa et al. [1962]	Socorro, New Mexico, USA (34°N)	3 summer night thunderstorms	193	26	14	6.4
Rakov et al. [1994]	Tampa, Florida, USA, (27.4°N)	3 convective summer thunderstorms	76	18	17	4.6
Cooray and Perez [1994]	Uppsala, Sweden (60°N)	2 frontal summer thunderstorms	137	10	18	3.4
Cooray and Jayaratne [1994]	Colombo, Sri Lanka, (12°N)	2 convective thunderstorms	81	12	21	4.5
Present study	São José dos Campos and Cachoeira, São Paulo, Brazil (23.2° and 22.6°S)	27 frontal and convective summer thunderstorms	233	16	20	3.8

Table 2. Duration of Observation and Some Parameters of Table 1 for a Subset of Thunderstorm Days in Brazil

Day	Duration of Thunderstorm Observation, min	Total Number of Flashes	Percent of Single-Stroke Flashes	Average Multiplicity
7 Nov. 2003	177	24	33	4.4
20 Dec. 2003	92	15	7	6.0
15 Jan. 2004	181	16	33	3.8
2 Feb. 2004	172	16	31	2.2
12 Feb. 2004	188	29	10	4.9
30 March 2004	185	42	7	3.8
Average of this subset			20.1	4.2

fifth leaders creating new paths to ground was 5% (3 in 61 fifth leaders) while no fifth leaders created new paths in the data observed in Florida. These differences are probably due to the higher amount of data observed in this work.

3.3.3. Effect of Number of Strokes in the Previous Channel

[26] The reason why second-order strokes have the greatest probability to create new channel is related to the poor consolidation of the channel after only one stroke. We consider a channel to be consolidated when it is capable of supporting the propagation of the following leader all the way to ground, resulting in a establishment of an unalterable path to ground. We have observed that out of 117 new channels, 106 (90.6%) occurred after the occurrence of only one stroke, 8 (6.8%) after two consecutive strokes have used the same channel, 2 (1.7%) after three, and contrary to what is reported by *Rakov et al.* [1994], we have observed the creation of a new channel after four consecutive strokes have participated in channel conditioning (0.9%). Although in Figure 7, three cases (5% of the fifth strokes) were responsible for the formation of a new channel, only one of them did so after 4 strokes using the same previous channel.

[27] *Valine and Krider* [2002] also observed some cases of new channel formation in stroke orders higher than 4 although the stroke order may be underestimated because of

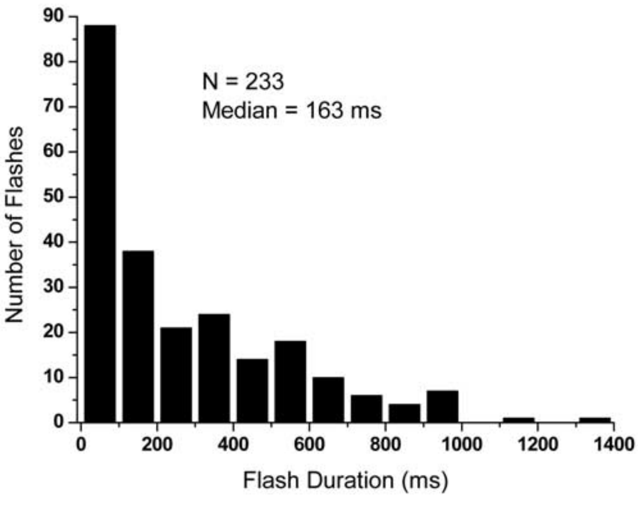

Figure 3. Histogram of number of flashes having a given flash duration.

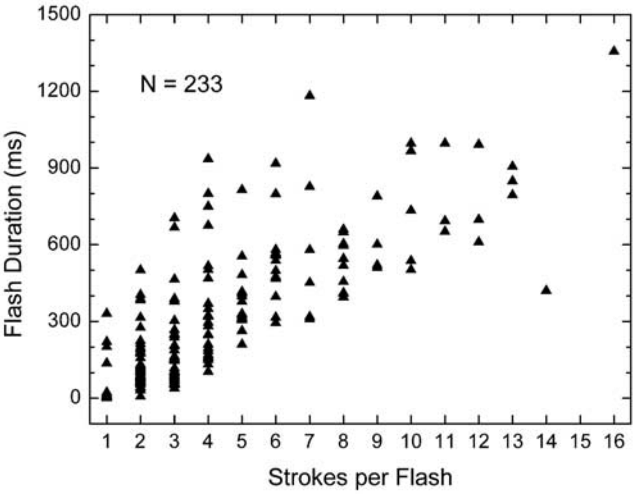

Figure 4. Scatterplot illustrating the relation between flash duration and the number of strokes per flash.

the lower resolution of their standard camera. They also reported the formation of a new channel after four strokes had conditioned the previous original channel. We believe that the higher number of flashes observed in this study and in that of *Valine and Krider* [2002] is responsible for the presence of these unusual observations.

[28] Six out of 138 (5%) had a stroke down a new channel (called B) that was followed by a subsequent stroke (A2) down the original previous channel (A1); see Table 3. In two of these flashes (1 and 2), this phenomenon occurred twice. Similar behavior was reported by *Thomson et al.* [1984] in 3% and by *Valine and Krider* [2002] in 2% of the flashes observed in their studies.

[29] Table 3 presents the time interval preceding the new channel (A1 to B) and the time interval preceding the following stroke that returns to the original channel (B to A2). Note that while the geometric mean (GM) of A1 to B is nearly equal to the GM of the interstroke time preceding all new channels (68 ms), the B to A2 interval is more than 2 times lower. A possible explanation for the lower GM value is that if it were longer, the original channel would be not conductive enough to be reused, a value estimated to be 100 ms by *Kitagawa et al.* [1962]. These observations support that it is not necessary to have a complete decay of channel conductivity in order for a new channel to form.

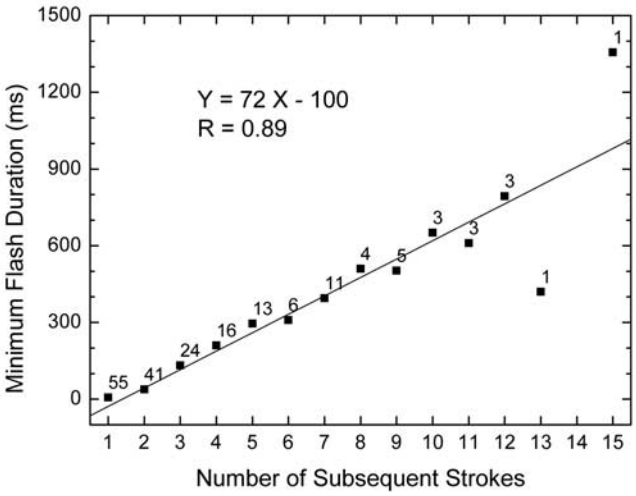

Figure 5. Minimum flash duration versus number of subsequent strokes. The numbers in the plot denote the total number of flashes that contained the given number of subsequent strokes. Also given are the correlation coefficient (R) and the regression equation.

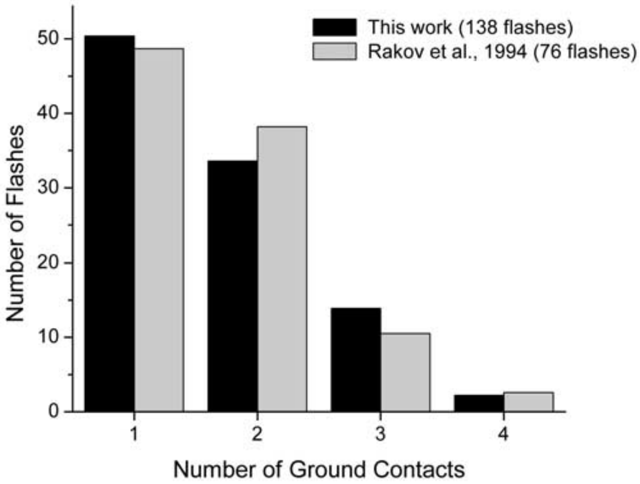

Figure 6. Number of flashes that produced the given number of ground strike points in this study and in Florida [*Rakov et al.*, 1994].

3.4. Interstroke Intervals

[30] The 608 time intervals between strokes in 186 negative multiple-stroke flashes presented a geometric mean value of 61 ms and an arithmetic mean value of 83 ms. The distribution of these intervals is shown in Figure 8. The maximum interval time between strokes was 782 ms and the minimum was 2 ms. This maximum value occurred between the second and third stroke of a negative flash. The

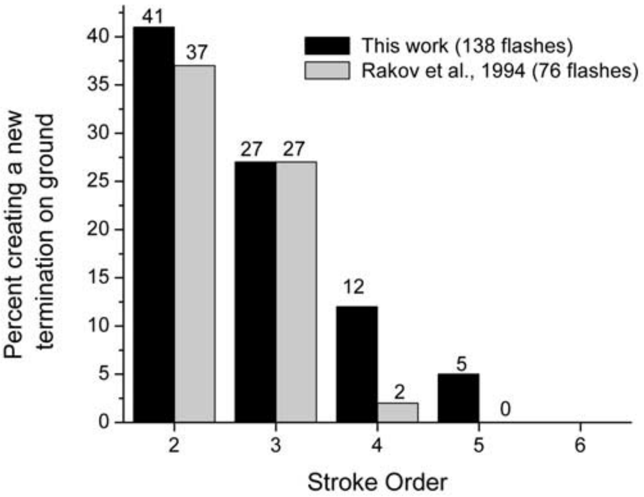

Figure 7. Probability of creating a new termination on ground by strokes of different order. The numbers on the bars represent the percentage.

Table 3. Time Interval Between Strokes Alternating Between Channels[a]

	Event								
	1a	1b	2a	2b	3	4	5	6	GM
A1 to B, ms	100	40	39	52	94	72	41	48	57
B to A2, ms	12	15	16	32	35	37	43	25	24
A1 to A2, ms	112	55	55	84	129	109	84	73	84

[a] A1 is the stroke that uses the original channel, B is the stroke forming a new channel, and A2 is the stroke that returns to the original channel. GM, geometric mean.

second stroke was followed by a continuing current of 542 ms, which partly explains why this interval was so large. The distribution shown in Figure 8 supports, in more than 99.5% of the cases, the criterion of maximum 500 ms between strokes largely used by lightning detection networks [see, e.g., *Cummins et al.*, 1998; *Rakov and Uman*, 1990].

[31] Another important characteristic of this distribution is that 19% of the interstroke intervals presented values less than 33 ms. This is time duration of the uncertainty window of standard video images even if odds and evens fields of the frames are analyzed separately [*Thomson et al.*, 1984]. Two strokes along the same channel separated by a short interval might fail to be individually distinguished if they occur within one field or if they appear in adjacent fields. In the latter case, without substantially increased luminosity evident in the video record, the second field image would be interpreted as continuing current following the earlier stroke [*Idone et al.*, 1998]. This means that 19% of the total number of strokes could have been missed if we used only standard video recording. A similar result, 18%, was obtained by *Thomson et al.* [1984], who used a wide band electric field change recording system as an auxiliary technique in the identification process of strokes recorded by standard cameras.

[32] In order to study the differences in interstroke intervals preceding strokes down the same channel and down new channel we plotted the histograms and calculated the geometric means of the two smaller subsets (Figure 9). Again, only subsequent strokes with clearly visible channels were used. Both histograms follow a lognormal distribution.

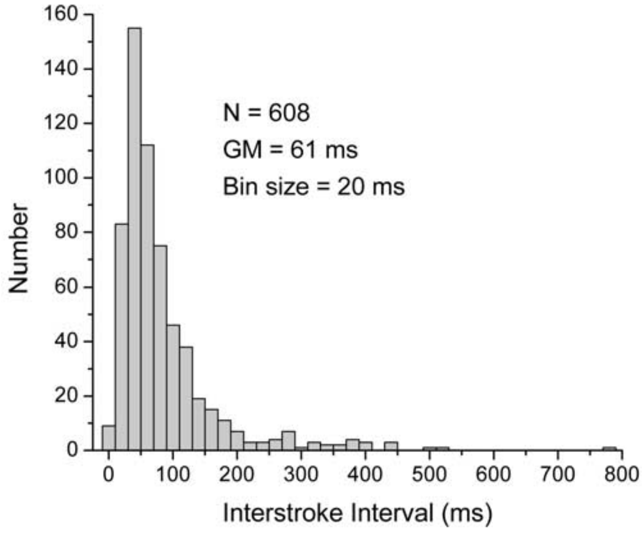

Figure 8. Interstroke interval distribution. GM means geometric mean.

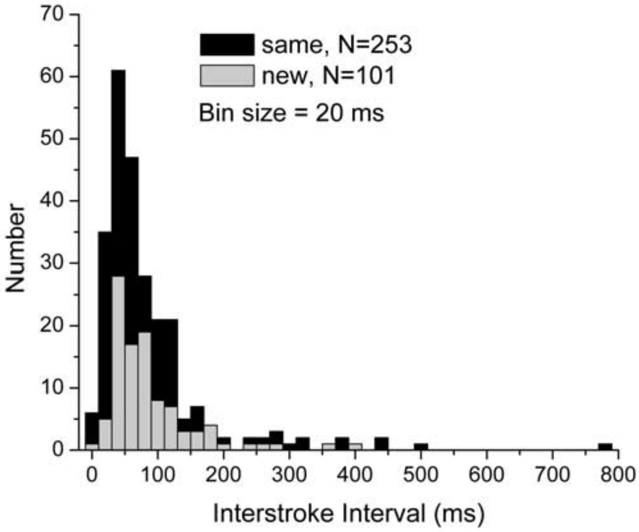

Figure 9. Interstroke interval distribution for same and new channels.

[33] Table 4 summarizes some parameters of these distributions and similar ones reported by *Rakov et al.* [1994]. The statistical values obtained in this study are similar to the ones obtained by *Rakov et al.* [1994]. The major difference is in the value of the time interval preceding subsequent strokes that create a new termination. Although it tends to be greater than interval between subsequent strokes that follows the previously formed channel, the difference was not significant at the 5% level of confidence for the Student *t* test. Note that in our study the sample size for new terminations events is almost 3 times larger than that used by *Rakov et al.* [1994]. We suggest that the mechanism governing the interstroke interval is independent of whether a subsequent leader follows the previously formed channel or a new channel. With the high-speed camera it was possible to observe several cases of stepped leaders or dart-stepped leaders creating new channels shortly after the occurrence of the previous stroke (see Figure 10).

3.5. Continuing Current

[34] *Kitagawa et al.* [1962] and *Brook et al.* [1962] defined "long" continuing current as indicated by a steady electric field change with a duration in excess of 40 ms, the value accepted at that time as a typical interstroke interval. *Shindo and Uman* [1989] defined "short" continuing current as indicated by similar field change with a duration between 10 ms and 40 ms, and also defined a new category of possible continuing current, "questionable" continuing current, as indicated by a similar field change with a duration between 1 and 10 ms. They chose to use this termination because the ramplike field changes could well be due to in-cloud processes, or to cloud-to-ground processes different from continuing current. Note that usually the duration of continuing currents in this type of study is underestimated when determining the instant at which the continuing current ends.

Table 4. Statistical Summary of Interstroke Intervals

	Present Study[a]			*Rakov et al.* [1994][a]		
	N	GM, ms	$\sigma_{\log}$	*N*	GM, ms	$\sigma_{\log}$
All subsequent strokes	608	61	0.34	270	60	0.35
Subsequent strokes in previously formed channel	253[b]	60	0.36	232	56	0.35
Subsequent strokes creating a new termination	101[b]	68	0.31	38	92	0.30

[a] *N* is the sample size, GM is the geometric mean, and $\sigma_{\log}$ is the standard deviation for $\log_{10} x$.
[b] Only subsequent strokes with clearly visible channels.

[35] Continuing current observations for studies using only standard video cameras has serious limitations, even if restricted to the study of long continuing currents [see *Valine and Krider*, 2002]. To observe continuing currents with duration less than 10 ms, high-speed or streak cameras are necessary. Using a high-speed camera, we could actually see these continuing currents and define them as "very short" continuing currents if their duration is less than 10 ms [see also *Ballarotti et al.*, 2005].

[36] A histogram showing the distribution of the duration of the continuing currents is given in Figure 11. Note the presence of an extreme value of 542 ms, this is the longest continuing current reported in the literature together with one event with similar duration (between 520 and 560 ms) shown in a histogram done by *Ogawa* [1995, Figure 4.3.10]. The value 1 ms was not computed in the histograms because it could contain the stroke current tail in approximately 10% of the strokes (considering a typical stroke duration of 100 μs and the frame exposure time of 1 ms). As in the study of the continuing current by means of electric field changes, the duration of the continuing currents may be also underestimated in the present study. The presence of rain is the main factor that may obstruct very faint luminosity produced by distant or small continuing currents.

[37] Three flashes had two strokes followed by long continuing currents. Similar observations were made by *Valine and Krider* [2002]. The thunderstorm that produced these three flashes had 33% of the recorded flashes with long continuing current (10 of 30 flashes). The second thunderstorm that had a higher percentage of occurrence of long continuing current had only 12.5% (5 of 42 flashes). We can speculate that the higher occurrence of long continuing current is related to the availability of charges in the negative charge layer of the thunderstorm and thus to the horizontal extent of the thundercloud.

3.5.1. Effect of Stroke Order

[38] The percentage of strokes followed by continuing currents versus stroke order is given in Figure 12. Almost 50% of any stroke, independently of its order, is followed by some kind of continuing current (with duration greater than 1 ms); 35.6% of the strokes were followed by short or long continuing currents, a percentage similar to the percentage of 36.6% found by *Shindo and Uman* [1989]. None of the 27 strokes of order 11 to 16 were followed by long continuing current, and none of the 31 strokes of order 7 were followed by either short or long continuing current.

[39] Only one first stroke of 186 multiple-stroke flashes and four of 47 single flashes were followed by long continuing current. This is in agreement with the statement that long continuing currents following the first stroke of multiple-stroke flashes are rare. Only two cases were observed by *Rakov and Uman* [1990] and none were reported by *Kitagawa et al.* [1962] and *Shindo and Uman* [1989]. We also observed that twelve first strokes were followed by short continuing current (8 first strokes of multiple flashes and 4 single stroke flashes).

3.5.2. Duration of Previous Interstroke Interval

[40] The geometric mean of interstroke time preceding 40 strokes followed by long continuing current (41 ms; $\sigma_{\log}$ = 0.24) is lower than the GM for all intervals (61 ms; $\sigma_{\log}$ = 0.34). These distributions follow a lognormal and are significantly different at the 5% level of confidence for the t test. Similar results were also observed by *Rakov and Uman* [1990] and *Shindo and Uman* [1989] for Florida and New Mexico.

4. Summary

[41] In this paper, we have proposed a new technique as an accurate means of discerning important CG lightning

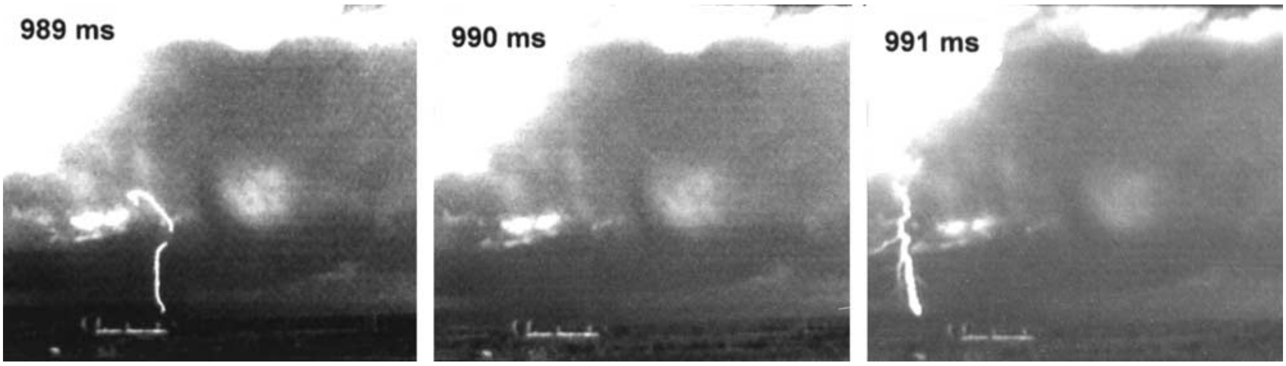

Figure 10. High-speed video image sequence of a flash showing two different channels separated by a time interval of approximately 2 ms.

characteristics. The accurate measurements of these characteristics of lightning are presented for the first time in Brazil, and are of considerable importance not only for the assessment of geographical differences hypotheses concerning the research of lightning but also for the electric utility industry and other users that benefit from lightning data.

[42] Within 233 CG flashes identified as negative flashes, 20% were single-stroke flashes and the average number of strokes per flash was 3.8. Both the percentage of single-stroke flashes and the average number of strokes per flash presented a significant variation from storm to storm. In a smaller subset, 51% of 138 flashes had multiple terminations on ground and produced 235 different strike points; therefore the average number of strike points per CG flash was 1.70. From the average multiplicity and from the average number of strike points per flash, we could say that each ground contact point is, on average, struck 2.2 times (a parameter that is useful in lightning protection). Of the new strike points, 41% were produced by the second stroke in the flash, and 91% of the changes in channel geometry occurred after there had been just one stroke in the previous channel. The 608 time intervals between strokes flashes presented a geometric mean value of 61 ms. Although the value of the time interval preceding subsequent strokes that create a new termination tends to be greater than interval between subsequent strokes that follows the previously formed channel, the difference was not statistically significant. A very small interstroke interval (2 ms) was observed between consecutive strokes connecting ground in different places. We conclude that the effect of the number of times that the channel is used is much more influent in determining if a new channel will be formed or not than the effect of the time elapsed from the preceding return stroke.

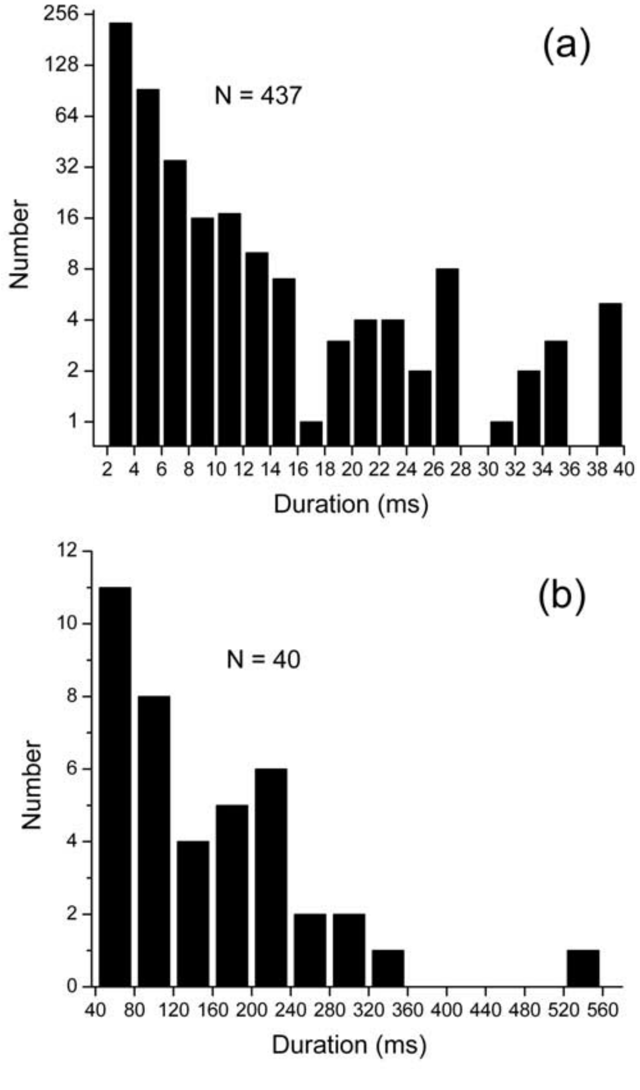

Figure 11. Histograms showing the distribution of continuing current duration (a) under and (b) above 40 ms.

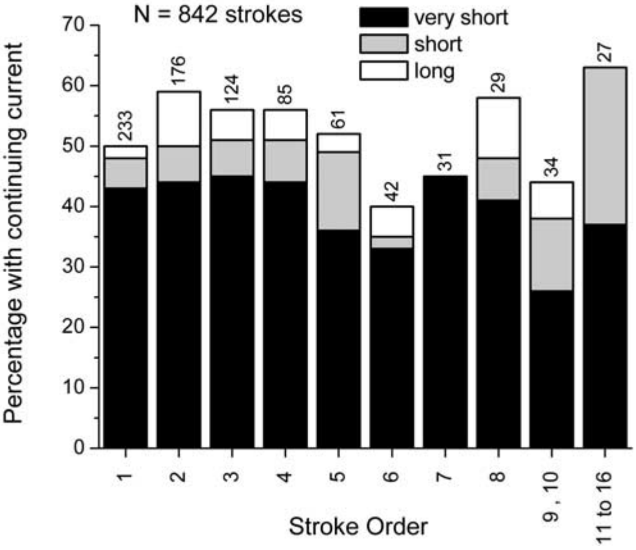

Figure 12. Occurrence of continuing current in strokes of different order. The numbers above the histogram denote the total number of strokes in each histogram bin.

[43] Almost 50% of any observed stroke, independently of its order, is followed by some kind of continuing current greater than 1 ms. A strong positive correlation between the number of subsequent strokes in a flash and the flash minimum duration seen was found. This correlation indicates that processes concerning the time requisite for the channel decay and for the positive leader in the cloud to provide more charges for the next stroke do not permit multiple strokes to occur under a certain minimum time duration. More duration data for higher-stroke flashes must be obtained in order to assure that this is tendency is also valid for higher-multiplicity flashes.

[44] In future we plan to use high-speed camera in conjunction with fast and slow electric field sensors in order to have more complete data on the lightning processes studied in this work.

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