High-speed camera observations of negative ground flashes on a millisecond-scale

M. G. Ballarotti, M. M. F. Saba, and O. Pinto Jr.
National Institute of Space Research (INPE), São José dos Campos, Brazil

Received 22 June 2005; revised 22 September 2005; accepted 5 October 2005; published 2 December 2005.

[1] A study of cloud-to-ground lightning characteristics based on high-speed camera observations of 455 flashes related to 40 thunderstorms is presented. The Brazilian Lightning Location Network (RINDAT) was used to calculate the polarity and the distance of the flashes to the camera. In some cases, a fast electric field flat antenna was also used to calculate the time difference between strokes on a microsecond-scale. Some general features of the data set are briefly presented. This paper is focused on two specific characteristics observed in video records with a frame a rate of 1,000 frames/s: (*i*) six strokes presenting two ground terminations that were simultaneously connected for some milliseconds, (*ii*) and a high number of continuing current occurrences with durations less than 10 ms. **Citation:** Ballarotti, M. G., M. M. F. Saba, and O. Pinto Jr. (2005), High-speed camera observations of negative ground flashes on a millisecond-scale, *Geophys. Res. Lett.*, *32*, L23802, doi:10.1029/2005GL023889.

1. Introduction

[2] Many studies of cloud-to-ground (CG) lightning characteristics on a millisecond-scale have been reported in the literature. Statistical studies of continuing current (CC) duration were done by several authors [e.g., *Kitagawa et al.*, 1962; *Thomson*, 1980; *Shindo and Uman*, 1989; *Rakov and Uman*, 1990a] based on TV and electric field observations. *Ballarotti et al.* [2004] presented for the first time CC duration measurements based on a digital high-speed camera for a reasonable number of events. The CC durations presented in these papers ranged from units to hundreds of milliseconds. *Malan and Collens* [1937], *Schonland et al.* [1938] and *Schonland* [1956] have discussed the luminous development of lightning and the formation of multiple ground contacts based on streak photography. *Rakov and Uman* [1994] made an important analysis of strokes separated in time by a millisecond or less based on electric field and TV records. *Rakov et al.* [1994], *Valine and Krider* [2002], *Parker and Krider* [2003], and *Qie et al.* [2005], among others, reported important results about lightning with multiple terminations on ground based on simultaneous TV and electric field records, and TV observations only. Results concerning the channel conditioning were also discussed by *Rakov et al.* [1994].

[3] *Kitagawa et al.* [1962] and *Brook et al.* [1962] defined "long" CC as indicated by a steady electric field change with duration in excess of 40 ms, the value accepted at that time as a typical interstroke interval. *Shindo and Uman* [1989] defined "short" CC as indicated by similar field change with a duration between 10 ms and 40 ms, and also defined a new category of possible CC, "questionable" continuing current, as indicated by a similar field change with a duration between 1 and 10 ms. They chose to use this terminology because the ramp like field changes could well be due to in-cloud processes, or to cloud-ground processes different from continuing current. Some authors had measured CC durations less than 10 ms [e.g., *Thomson*, 1980; *Shindo and Uman*, 1989] based essentially on slow electric field records. In some cases, such signatures could also be due to cloud processes and not only to continuing current. High-speed imaging records are not subject to this misinterpretation, so what were called "questionable" continuing currents by *Shindo and Uman* [1989], we are now defining as "very short" continuing currents if their duration is less than 10 ms.

[4] Two important points related to the duration measurement of very short CC involved in this type of study must be pointed out: (a) the duration of continuing currents is usually underestimated when determining the instant at which it ends, and (b) an overestimation may also be done if we consider that the maximum duration of the return stroke is often assumed to be about 3 ms, what could contaminate the CC by what could be just return-stroke pulse tails. In this delicate range below 10 ms, the discrimination between return stroke tails and beginning of a CC is very difficult, even in a direct current measurement, and "...is apparently related to the source of the charge transported to ground... The return stroke removes charge deposited on the channel by a preceding leader, whereas CC is likely to be associated with the tapping of fresh charge regions in the cloud." [*Rakov and Uman*, 2003, p. 176]. The observations reported here were not able to make this type of discrimination and an adopted time criterion to reduce such contamination is presented in section 3.2.

[5] This paper is focused on two interesting features of negative CG flashes: (*i*) the presence of CC with durations of few milliseconds in hundreds of strokes; and (*ii*) some strokes with two strike points simultaneously connected for some milliseconds long. As far as we know, no similar results based on digital imagery records were published in the literature.

2. Instrumentation and Measurements

[6] A high-speed digital video camera (Red Lake Motion Scope 8000S) having a time resolution and a time exposure of 1 ms was used by the Atmospheric Electricity Group (ELAT) to record images of cloud-to-ground flashes over

0094-8276/05/2005GL023889

Table 1. Events of Ground Flashes With Two Strike Points Simultaneously Connected for Some Milliseconds Long[a]

Flash #	Duration of 1st and 2nd Contacts	Stroke Order Involved	Contact That Lasts Longer	Time Between Strike Points
123	2 ms (both)	1st	-	<1 ms
166	6 and 1 ms	2nd	1st	<2 ms
221	5 and 177 ms	1st	-	<1 ms
326	2 and 3 ms	1st	-	<1 ms
414	5 and 2 ms	1st	1st	31 μs
436	3 and 1 ms	4th	1st	253 μs

[a]The duration of double-ground contacts is given by the lower value in second column.

Paraíba Valley (São Paulo State) between January 2003 and April 2005. The CCD of the video camera operated without its original infrared filter, and all images were GPS synchronized and time stamped. The triggering system was operated manually for each flash. The camera recorded 1.0 sec before and 1.0 sec after trigger, resulting in a video total duration of 2.0 sec per event (2,000 frames).

[7] As an auxiliary instrument, we used the RINDAT - Integrated National Lightning Detection Network data in order to identify the stroke polarity. The stroke matching between camera and network was done by GPS time synchronization.

[8] A fast electric field flat-plate antenna was also used in this study to observe some flashes. Its bandwidth was from 306 Hz to 1.5 MHz and the sample rate used was 5 MS/sec. The acquisition module used was a National Instruments PCI-6110, 12-Bit with 4 analog inputs.

[9] A total of 455 flashes (in 40 different thunderstorms) was observed from two sites: one located in São José dos Campos City and other in Cachoeira Paulista City (both in Paraíba Valley, São Paulo State, southeast Brazil). 78% of all CG flashes recorded were detected by RINDAT.

3. Results and Discussion

[10] In order to provide an overview of the dataset used in this paper, we report in the following some lightning parameters found in the observations. The interstroke interval ranged from 31 μs to 782 ms and the CC duration ranged from one to 541 ms (this maximum value corresponding to the maximum interstroke interval cited above). The geometric mean for interstroke intervals was 61 ms. Considering values greater or equal to 3 ms, the CC geometric mean duration was 11.8 ms, the mean was 32.3 ms and the median was 7.0 ms. The average number of strokes per flash was 3.8 for negative ground flashes. The maximum values for stroke multiplicity was 18 and for channel multiplicity was 5. The creation of new termination on ground occurred in stroke orders from 2 to 5. Such an occurrence on the 5th order was reported also by *Shao et al.* [1995] that also used an accurate-stroke-count technique (as defined by *Rakov and Huffines* [2003]).

[11] One specific flash, the flash named 123, was an unusual event in several aspects. Its multiplicity was 12 and the total duration was 992 ms. Its 10th and 11th strokes contained continuing currents of 22 and 26 ms, respectively. But the most peculiar and interesting characteristic of this flash was the formation of a new termination on ground after 4 consecutive strokes occurred in the same channel. This observation confirms a similar one done by *Valine and Krider* [2002], indicating that even after four consecutive strokes have occurred in a same channel, an unalterable path to ground is still not established.

[12] In the flash 123, two aspects seems to favor such occurrence: (*i*) its first stroke contacted ground simultaneously in two different points – this could "divide" the total current and, consequently, weakened the channel conditioning; and (*ii*) a large interstroke interval of 251 ms (without CC) preceded the 5th stroke, which created the new termination on ground. We understand that usually, considering a typical leader-return stroke sequence for the first stroke and an interstroke interval not too large, four consecutive strokes is sufficient to produce an unalterable channel to ground.

[13] Still concerning channel conditioning, we report here the probability of creating a new termination on ground after different number of channel utilizations. We used in this analysis a subset of 117 new ground termination cases (based only on camera records), which we could clearly identify the ground contact point. In 90.6% of the cases, only one stroke occurred in the channel before creating a new termination; 6.8% for two channel utilizations; 1.7% for three and 0.9% for four. The vast majority (90.6%) of the new terminations were created after there had been just one stroke in the previous channel. This result shows that the channel conditioning depends specially on the number

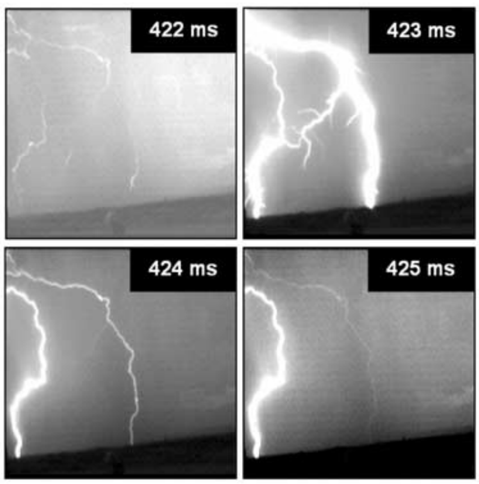

Figure 1. Frame sequence of flash 221 occurred at 01mar04. The left termination had a long CC of 177 ms. Note that in frame 423 ms both terminations were connected, showing that the time interval between connections was certainly smaller than the frame time exposure (1 ms).

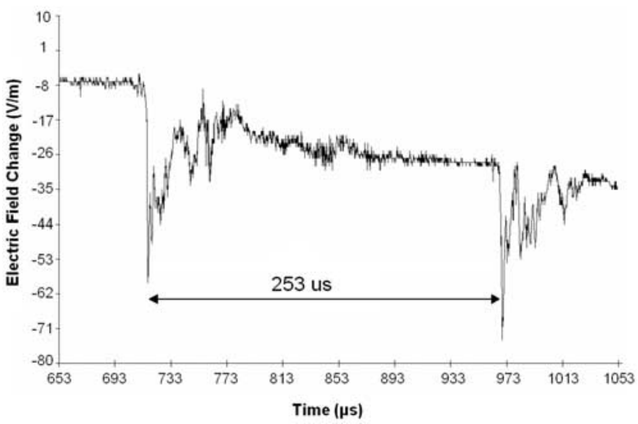

Figure 2. Electric field change record of the forked stroke of flash 436 occurred at 23mar05.

of consecutive strokes that occurred in the channel. Other authors [e.g., *Thomson et al.*, 1984; *Saba et al.*, 2005] have already concluded that time intervals involving (a) a same channel and (b) different channels don't differ significantly from each other (t-Student test at 0.05 level). This idea is in strong agreement with *Rakov and Uman* [1990b] suggestion that "the channel status depends not only on the time elapsed from the previous return stroke (channel age) but also on the number of strokes that conditioned the channel previously".

3.1. Two Strike Points Simultaneously Connected for Some Milliseconds Long: An Evidence of a Forked Stroke Occurrence

[14] Single strokes creating two terminations on ground were already described by some authors [e.g., *Schonland et al.*, 1935; *Guo and Krider*, 1982; *Rakov and Uman*, 1994; *Willett et al.*, 1995; *Wang et al.*, 2000; *Qie et al.*, 2005]. We present in this paper six flashes where two channels remained connected to ground simultaneously during some milliseconds, and the time difference between these two connections were, except for one case (flash 166), certainly smaller than 1 ms (based on our high-speed camera records and, for some cases, also on the fast electric field records). Thus, the forked channel evidence in this work is based on the observation of 2 contact points on 2 or more sequential frames of the high-speed camera. The results are summarized in Table 1. Both terminations involved in all of these cases were new ground strike points (stepped leader–return stroke sequence).

[15] An example of forked stroke is shown in Figure 1 for flash 221. In a typical stepped-leader-return-stroke sequence, all leader branches are inhibited to propagate after a ground connection. On the other hand, when a branch leader tip is too close to the ground attachment and the stroke has already begun, there is no sufficient time to this inhibition and a single stroke creates two terminations on ground, i.e., a forked stroke occurs.

[16] The forked stroke was observed in stroke orders 1, 2 and 4, but more frequently in first order (66%). In three cases it was possible to identify which connection was first, and, in all of them, the first channel lasted longer, showing prevalence. The current flowing in these first tens or even some hundreds of microseconds (after the first connection) before the beginning of the second connection seems to enable a channel more conductive (or less resistive) for the further CC flow. This seems to be the main reason for this prevalence, which, by the way, appears to be characteristic of a forked stroke.

[17] The longest simultaneous ground termination duration observed was of 5 ms for flash 221, shown in Figure 1. This parameter seems not to exceed several units of milliseconds; otherwise, it could have been observed in some of the several studies already done based on standard VHS camera (17 ms interval between frames).

[18] Figure 2 exhibits the electric field record of the forked stroke of flash 436, indicating the time interval between strike points (initial peaks).

3.2. Continuing Current Observations With Duration Less Than 10 ms

[19] In this analysis, a subset of 890 strokes was selected, corresponding to 233 negative CG flashes observed in the beginning of the period of study. Figure 2 shows a stroke, which also contained in the right termination a very short CC.

[20] Of 890 strokes, 650 (73%) presented some luminosity persistence after the return stroke frame and 553 (62%) presented some luminosity persistence with durations below 10 ms. Considering the limitations of the measurements, we limited this study about the defined "very short CC" to continuing luminosity durations between 3 and 10 ms. They are present in 17% (154) of all 890 strokes and their geometric mean duration is 5.3 ms. Figure 3 shows a histogram of the CC durations observed in the specific range of 3 to 10 ms. 28% of all strokes contained some type of CC (very short, short or long).

[21] It is important to remember that the distance of observation varied from few to 80 km (based on RINDAT reprocessed solutions). In some thunderstorms, due to the large distance and the influence of rain, the duration of the very short CC was certainly underestimated. This aspect makes us understand that, in reality, the percentage of very short CC occurrences is probably greater than the presented value.

[22] Our results about very short CC are in agreement with the suggestion given by *Mazur et al.* [1995] that: "The video and electric field observations indicate that all return

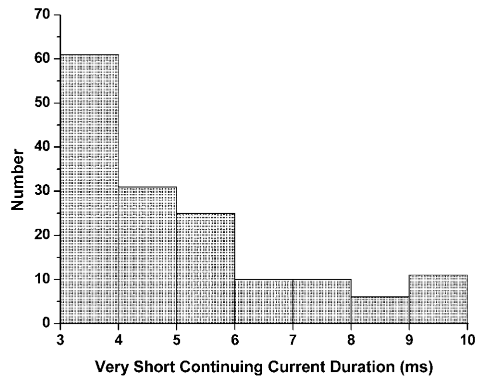

Figure 3. Histogram of very short CC durations observed. This distribution exhibited a lognormal behavior.

strokes have at least a short continuing current, of the order of one or a few milliseconds.''

4. Concluding Remarks

[23] Some general characteristics of negative ground flashes observed were briefly presented (interstroke intervals, continuing current durations, stroke multiplicity and occurrences of new ground terminations on ground), based on high-speed camera observations of negative ground lightning. One atypical flash was analyzed, which had a new ground termination after 4 strokes in the same channel. Regarding channel conditioning, the probability of creating a new termination on ground after different number of channel utilizations was presented. The vast majority (90.6%) of the new terminations were created after there had been just one stroke in the previous channel.

[24] Two aspects of the negative ground flash on a millisecond-scale were analyzed. The first one was about the two simultaneous ground contacts for 6 stroke cases, indicating the occurrence of a forked stroke. This feature is based on observation of 2 contact points on 2 or more sequential frames of the high-speed camera. Simultaneous contacts seem to last only for a few ms (the longest simultaneous ground termination duration observed was 5 ms), and the first contact also shows some prevalence. More observations based on a high-speed camera and a fast electric field records are required for a better understanding and statistics of the forked stroke.

[25] The second analysis was about continuing current duration less than 10 ms – which we called very short CC. 17% of all strokes presented very short CC between 3 and 10 ms, a higher occurrence if compared with short and long occurrences together (11%). In order to discriminate more precisely the end of the return stroke and the beginning of the CC for a considerable amount of cases, measurements of the channel luminosity as a function of height would be useful instead of only a time criterion, as adopted in this work.

[26] **Acknowledgments.** We would like to thank W. Schulz from ALDIS (Austria) for sharing their electric field antenna with us; to E. C. Ferraz, F. G. Cardoso, G. F. Cabral and R. Faria for their help in the data acquisition and reduction; to K. P. Naccarato for obtaining the RINDAT data; to FAPESP for the research grant # 02/10630-7 and to Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) research grant # 475299/2003-5; also to V. Mazur and I. R. C. A. Pinto for the fruitful discussions.

References

Ballarotti, M. G., M. M. F. Saba, and O. Pinto Jr. (2004), First observations of negative lightning continuing current in Brazil, paper presented at 1st International Conference on Lightning Physics and Effects, Braz. Soc. for Electr. Prot., Belo Horizonte, Brazil.

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

Guo, C., and E. P. Krider (1982), The optical and radiation field signatures produced by lightning return strokes, *J. Geophys. Res.*, *87*, 8913–8922.

Kitagawa, N., M. Brook, and E. J. Workman (1962), Continuing current in cloud-to-ground lightning discharges, *J. Geophys. Res.*, *67*, 637–647.

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

Mazur, V., P. R. Krehbiel, and X.-M. Shao (1995), Correlated high-speed video and interferometric observations of a cloud-to-ground flash, *J. Geophys. Res.*, *100*, 25,731–25,753.

Parker, N. G., and E. P. Krider (2003), A portable, PC-based system for making optical and electromagnetic measurements of lightning, *J. Appl. Meteorol.*, *42*, 739–751.

Qie, X., X. Kong, G. Zhang, T. Zhang, T. Yuan, Y. Zhou, Y. Zhang, H. Wang, and A. Sun (2005), The possible charge structure of thunderstorm and lightning discharges in northeastern verge of Qinghai–Tibetan Plateau, *Atmos. Res.*, *76*, 231–246.

Rakov, V. A., and G. R. Huffines (2003), Return-stroke multiplicity of negative cloud-to-ground lightning flashes, *J. Appl. Meteorol.*, *42*, 1455–1462.

Rakov, V. A., and M. A. Uman (1990a), Long continuing current in negative lightning ground flashes, *J. Geophys. Res.*, *95*, 5455–5470.

Rakov, V. A., and M. A. Uman (1990b), Some properties of negative cloud-to-ground lightning flashes versus stroke order, *J. Geophys. Res.*, *95*, 5447–5453.

Rakov, V. A., and M. A. Uman (1994), Origin of lightning electric field signatures showing two return-stroke waveforms separated in time by a millisecond or less, *J. Geophys. Res.*, *99*, 8157–8165.

Rakov, V. A., and M. A. Uman (2003), *Lightning: Physics and Effects*, 687 pp., Cambridge Univ. Press, New York.

Rakov, V. A., M. A. Uman, and R. Thottappillil (1994), Review of lightning properties from electric field and TV observations, *J. Geophys. Res.*, *99*, 10,745–10,750.

Saba, M. M. F., M. G. Ballarotti, and O. Pinto Jr. (2005), Negative cloud-to-ground lightning properties from high-speed video observations, *J. Geophys. Res.*, doi:10.1029/2005JD006415, in press.

Schonland, B. F. J. (1956), The lightning discharge, *Handb. Phys.*, *22*, 576–628.

Schonland, B. F. J., D. J. Malan, and H. Collens (1935), Progressive lightning, II, *Proc. R. Soc. London, Ser. A*, *152*, 595–625.

Schonland, B. F. J., D. J. Malan, and H. Collens (1938), Progressive lightning, IV, *Proc. R. Soc. London*, *168*, 455–469.

Shao, X. M., P. R. Krehbiel, R. J. Thomas, and W. Rison (1995), Radio interferometric observations of cloud-to-ground lightning phenomena in Florida, *J. Geophys. Res.*, *100*, 2749–2783.

Shindo, T., and M. A. Uman (1989), Continuing current in negative cloud-to-ground lightning, *J. Geophys. Res.*, *94*, 5189–5198.

Thomson, E. M. (1980), Characteristics of Port Moresby ground flashes, *J. Geophys. Res.*, *85*, 1027–1036.

Thomson, E. M., M. A. Galib, M. A. Uman, W. H. Beasley, and M. J. Master (1984), Some features of strokes occurrence in Florida lightning flashes, *J. Geophys. Res.*, *89*, 4910–4916.

Valine, W. C., and E. P. Krider (2002), Statistics and characteristics of cloud-to-ground lightning with multiple ground contacts, *J. Geophys. Res.*, *107*(D20), 4441, doi:10.1029/2001JD001360.

Wang, D., N. Takagi, T. Watanabe, V. A. Rakov, and M. A. Uman (2000), Luminosity waves in branched channels of two negative lightning flashes, *J. Atmos. Electr. Jpn.*, *20*, 91–97.

Willett, J. C., D. M. LeVine, and V. P. Idone (1995), Lightning-channel morphology revealed by return-stroke radiation field waveforms, *J. Geophys. Res.*, *100*, 2727–2738.

M. G. Ballarotti, O. Pinto Jr., and M. M. F. Saba, National Institute of Space Research (INPE), São José dos Campos, Brazil. (mgballa@dge.inpe.br)