Pulse trains that are characteristic of preliminary breakdown in cloud-to-ground lightning but are not followed by return stroke pulses

Amitabh Nag¹ and Vladimir A. Rakov¹

Received 1 February 2007; revised 26 May 2007; accepted 4 September 2007; published 8 January 2008.

[1] In this study, we identify and examine electric field pulse trains that are characteristic of preliminary breakdown in negative cloud-to-ground discharges but are not followed by return stroke waveforms. We assume that such trains are manifestations of the initiation of downward negative stepped leaders that fail to propagate all the way to the ground and refer to these events as “attempted first cloud-to-ground leaders,” although some of them were followed by full-fledged cloud discharges. We examined a total of 2475 electric field records of lightning events acquired in Gainesville, Florida, in 2006, and waveforms in 33 of them were found to satisfy criteria set for attempted cloud-to-ground leaders. In addition to pronounced bipolar pulses with positive (atmospheric electricity sign convention) initial half cycle, negative unipolar and negative (initial half cycle) bipolar pulses were sometimes seen toward the end of the train. We also observed that at the beginning and at the end of the pulse train, there were narrower pulses, often having durations in the range of 1–2 μs, which are more than an order of magnitude shorter than for “classical” preliminary breakdown pulses. The arithmetic mean of total pulse train durations is 2.7 ms, and the weighted arithmetic means of individual pulse durations and interpulse intervals are 17 and 73 μs, respectively. Some of the attempted cloud-to-ground leaders, which should belong to the cloud discharge category, can be misclassified as negative cloud-to-ground discharges by lightning locating systems such as the U.S. National Lightning Detection Network.

Citation: Nag, A., and V. A. Rakov (2008), Pulse trains that are characteristic of preliminary breakdown in cloud-to-ground lightning but are not followed by return stroke pulses, J. Geophys. Res., 113, D01102, doi:10.1029/2007JD008489.

1. Introduction

[2] The overall negative cloud-to-ground lightning discharge, often termed ground flash, consists of typically three to five component strokes or just strokes [Rakov and Uman, 2003]. Each stroke is composed of a downward moving leader and an upward moving return stroke. A leader initiating the first stroke in a flash exhibits stepping and is preceded by the initial or preliminary breakdown, which can be defined as the in-cloud process that initiates or leads to the initiation of the downward moving negative stepped leader. The initial breakdown involves the formation of a single channel or a sequence of channels. In the latter case, they extend in seemingly random directions from the cloud charge source with one of these channels evolving into the stepped leader which bridges the cloud charge source and the ground (e.g., Rhodes and Krehbiel [1989], Shao [1993], and a recent review by Rakov [2006]).

[3] The preliminary breakdown process in ground flashes sometimes (in 18% of 327 negative cloud-to-ground discharges in our auxiliary data set acquired for a separate study [Nag, 2007]) produces a train of relatively large microsecond-scale electric field pulses. The auxiliary data set corresponds to three consecutive storm days that were randomly selected from our overall database. An example of pronounced preliminary breakdown pulse train in a cloud-to-ground flash containing at least five strokes (there was a possibility of missing higher-order strokes due to limited record length) is shown in Figure 1. The time interval between the pulse train and the return stroke waveform is typically several milliseconds or more (geometric mean of 23 ms in our auxiliary data set). The electric field amplitude of the initial breakdown pulses can be comparable to or even exceed that of the corresponding first return stroke pulse.

[4] The characteristic features of preliminary breakdown pulse trains in negative cloud-to-ground flashes (based on information found in the literature) are as follows.

[5] 1. Duration of the pulse train: The entire duration of the preliminary breakdown pulse train is of the order of 1 ms [e.g., Rakov, 1999].

[6] 2. Regularity of pulses in a train: This is a subjective feature, but it has been noted by many researchers. According to Kitagawa and Brook [1960] and Weidman and Krider [1979], regularity of preliminary breakdown pulses and uniformity of time intervals between them in the case of cloud-to-ground flashes is higher than for cloud flashes.

[7] 3. Overall pulse shape: Individual preliminary breakdown pulses in the train are bipolar, as reported by many
investigators [e.g., Kitagawa, 1957; Clarence and Malan, 1957; Kitagawa and Kobayashi, 1959; Kitagawa and Brook, 1960; Krider and Radda, 1975; Weidman and Krider, 1979; Beasley et al., 1982; Gomes et al., 1998; Rakov, 1999].

4. Polarity of the initial half cycle: The initial polarity of bipolar pulses in the train is the same as that of negative return stroke pulses [e.g., Weidman and Krider, 1979]. For the atmospheric electricity sign convention [e.g., Rakov and Uman, 2003, pp. 8–9] this polarity is positive. In contrast, for the initial breakdown in cloud flashes, the dominant polarity of the initial half cycle of individual pulses is negative [e.g., Rakov, 1999].

5. Overall pulse duration: According to Rakov et al. [1996], the typical total duration of individual pulses in the train is in the range of 20 to 40 \( \mu s \). In contrast, for the initial breakdown in cloud flashes the typical total pulse duration is 50 to 80 \( \mu s \).

6. Interpulse interval: The typical time interval between individual pulses in the train is 70 to 130 \( \mu s \), versus 600 to 800 \( \mu s \) for initial breakdown in cloud flashes [Rakov et al., 1996].

[10] It is important to note that in about 82% of the electric field records of cloud-to-ground discharges in our auxiliary data set the initial breakdown pulses are either undetectable or have negligible amplitudes compared to that of the following return stroke pulse.

[11] In this study, we examine pulse trains that are characteristic of preliminary breakdown in negative cloud-to-ground discharges (see characteristic features listed above), but are not followed by return stroke waveforms. Examples of these trains, for four different classes discussed in section 3, are shown in Figures 2, 3, 4, and 5. We assume that such trains are manifestations of the initiation of downward negative stepped leaders that fail to propagate all the way to ground and refer to these events as attempted first cloud-to-ground leaders, although some of them were
followed by full-fledged cloud discharges. It is possible that some of our attempted leaders could also be classified as “inverted intracloud flashes,” occurring between the main negative and lower positive charge regions. In this latter case, the lower positive charge can be viewed as “blocking” the progression of descending negative leader from reaching ground and thus “converting” the potential cloud-to-ground flash to an intracloud one. Whatever the scenario, characteristics of preliminary breakdown–type pulses that we attributed to attempted leaders were indicative of a cloud-to-ground flash. Another possible interpretation of the observed pulse trains is a unique discharge process in the cloud that may or may not be followed by formation of a stepped-leader channel terminating (or not terminating) on ground.

[13] Note that Shao et al. [1995] used the term “attempted leaders” to denote subsequent leaders which did not make contact with ground, while in this paper the term “attempted leader” refers to the first (and only) leader following the preliminary breakdown process. Subsequent leaders usually follow previously created channels to ground and apparently do not involve a preliminary breakdown process at least of the type which occurs at the beginning of flash.

2. Methodology

[14] We will assume that the beginning of stepped leader is marked by preliminary breakdown pulses (when these pulses are detectable). Thus the time interval between the beginning of the preliminary breakdown pulse train and the first return stroke pulse in electric field record gives the duration of stepped leader, which is usually of the order of a few tens of milliseconds. A similar approach to finding stepped-leader duration was used by Brook [1992] and Heavner et al. [2002]. In order to obtain an estimate of stepped-leader duration using this approach, we used a sample of 59 electric field records of cloud-to-ground discharges showing pronounced preliminary breakdown pulse trains, from our auxiliary data set. Only those pulse

Figure 2. (a) Electric field record of an attempted leader with no pulse activity following the preliminary breakdown pulse train. (b) Preliminary breakdown–like pulses of the attempted leader shown in Figure 2a.
trains having at least three distinct pulses with peak-to-peak amplitudes equal to or exceeding twice that of the average noise level were considered. We found that only 12% (7 out of 59) of the leaders had durations greater than 55 ms and only about 5% (3 out of 59) of them had durations greater than 90 ms.

[15] Rakov and Uman [1990] measured leader durations using their overall electric field waveforms and reported that the overwhelming majority of leaders initiating negative first strokes in Florida had durations in the range from 20 to 90 ms. According to their Figure 10a, only about 3% of Florida stepped leaders are expected to have durations longer than 90 ms. This result is consistent with our finding that stepped leaders having durations longer than 90 ms are very rare. Note that geometric mean first-stroke leader durations in our and Rakov and Uman's studies were 23 ms (59 events) and 35 ms (71 events), respectively. Interestingly, our geometric mean of 23 ms is equal to the median time interval between the preliminary breakdown pulse train and the first stroke reported by Schulz and Diendorfer [2006] for 92 negative multiple-stroke flashes in Austria.

[16] On the basis of the above, we assume that the leader duration is unlikely to exceed 90 ms. Accordingly, if we identify a pulse train characteristic of preliminary breakdown in negative ground flashes, but this pulse train is not followed by return stroke pulses within 90 ms after the beginning of the train, we classify this event as an attempted cloud-to-ground leader. This criterion could be applied to a significant fraction (1073 out of 2475 records) of our main data set, for which the posttrigger time was 120 ms. However, in acquiring data analyzed here, we used different pretrigger/posttrigger times (see Table 1) that were needed for different projects. When our records were not long enough to examine 90 ms after the beginning of the preliminary breakdown pulse train, we had to reduce the assumed “maximum” leader duration (the time interval after the beginning of preliminary breakdown pulse train, during which we searched for return stroke waveforms). Such reduced “maximum” leader durations were 80 or 56 ms. This should not introduce a significant error, since
only about 12 to 18% of stepped leaders in Florida are expected to be longer than 55 ms, according to Rakov and Uman [1990] and our analysis described above. Over three quarters (76%; see Table 1) of attempted leaders were identified in records with posttrigger time of 120 ms. None of our conclusions would change if we excluded records with 80 and 56 ms posttriggers.

[17] The criteria for identification of preliminary breakdown pulse trains of attempted leaders are based on the characteristic features (described in section 1) of preliminary breakdown pulse trains in negative cloud-to-ground flashes. Similar to the approach used in examining pulse trains in cloud-to-ground discharges (see above), only those pulse trains, which had at least three distinct pulses that satisfied the criteria and peak-to-peak amplitudes equal to or exceeding twice that of the average noise level, have been considered in this study. Note that besides the characteristic (“classical”) pulses described above, preliminary breakdown pulse trains often contain other types of pulses, usually of considerably smaller amplitude and duration (see, for example, pulses occurring between 1.3 and 1.4 ms in Figure 6a and “narrow” pulses shown in Figure 7b). These “noncharacteristic” pulses were not used for identification of preliminary breakdown pulse trains, but were included in the overall characterization of pulse trains and individual pulses presented in section 4. Definitions of the various pulse train characteristics are illustrated in Figures 6a and 6b.

[18] Overall preliminary breakdown pulse train duration ($T_{PB}$) is defined as the time interval between the peaks of the first and last pulses in the train. Pulses were considered as not belonging to the pulse train if they were separated from the last pulse by at least 2 ms. Pulse duration ($T_{PW}$) is defined as the full width of the pulse, and interpulse interval ($T_{IP}$) is defined as the time interval between the peaks of two consecutive pulses.

3. Data

[19] Our main data set contains 2475 electric field records of lightning discharges that were acquired in Gainesville, Florida, in 2006 (on 24 and 28 May; 1, 2 and 3 June; and
15, 16 and 17 July). Using thunder ranging and the characteristic features of return stroke electric field waveforms at known distances in the 50 to 250 km range [Pavlick et al., 2002, Figure 5], we estimated that the majority of our records are due to lightning discharges occurring at distances ranging from a few to about a hundred kilometers.

The electric field measuring system included a circular flat plate antenna followed by an integrator and a unity gain, high-input impedance amplifier. The antenna was installed on the roof of a three-story building on the University of Florida campus. No amplitude calibration is available (primarily due to lack of knowledge of the building enhancement factor), but none of the results presented in the paper is affected by this. A Nicolet ISOBE 3000 fiber-optic link was used to transmit signals from the antenna and associated electronics to a LeCroy 8-bit digitizing oscilloscope which recorded the incoming signals in its memory unit. The system had a useful frequency bandwidth of 16 Hz to 10 MHz, the lower and upper limits being determined by the RC time constant of the integrator and the amplifier, respectively. The time constant (9.9 ms) was long enough for faithful reproduction of microsecond-scale pulses examined here. Sampling interval was 4 or 10 ns.

A summary of data used in this study is presented in Table 1. The number of nonlightning triggers was negligible; that is, essentially all the electric field records obtained and characterized in Table 1 were in response to some type of lightning activity. Further, each record corresponds to an individual lightning discharge, since the probability of system triggering more than once during the same lightning discharge was remote. Waveforms in 33 electric field records were found to satisfy the criteria set for attempted cloud-to-ground leaders. These are classified in Table 2, depending upon the pulse activity (or lack of such) following the preliminary breakdown pulse train and presence (or absence) of pronounced electrostatic field ramp. Pulses were treated as following the pulse train (as opposed to being part of the train) if they were separated from the last pulse of the train by at least 2 ms. Two of the 33 records contained two trains of preliminary breakdown pulses each, so that the total number of pulse trains analyzed here was 35.

Figure 5. (a) Electric field record of an attempted leader whose preliminary breakdown pulse train is followed by nonreturn stroke-type pulses (see inset) and static ramp. (b) Preliminary breakdown-like pulses of the attempted leader shown in Figure 5a.
The electric field associated with lightning discharges can be viewed as being composed of the electrostatic, induction, and radiation field components. At larger distances (beyond several tens of kilometers) and at early times the radiation field component is the dominant one. Microsecond-scale pulses can be viewed as being entirely due to this component. When the distance between the source and observer is relatively small (of the order of some kilometers), at later times the electrostatic field component can be dominant. The millisecond-scale ramp seen in 7 of the 33 electric field records exhibiting preliminary breakdown–type pulses analyzed here is due to this electrostatic component.

4. Analysis and Discussion

Temporally isolated short-duration (submillisecond) discharges were observed using the VHF Lightning Mapping Array by Krehbiel et al. [2003]. These discharges were described as occurring either as precursors of full-fledged lightning flashes or as “spatially limited or attempted breakdown events” and apparently were more commonly associated with the upper negative charge region and convective surges in anomalous (inverted polarity) storms. Maier et al. [1996] reported that 9.3% of their flashes detected by the VHF Lightning Detection and Ranging System (LDAR) at the Kennedy Space Center (KSC) had durations of less than 101 μs, the minimum time between consecutive LDAR sources. Defer et al. [2001], using a VHF interferometric lightning mapper, observed a particular type of lightning flashes (15% of the total number of flashes imaged during a storm in Nebraska-Colorado on 10 July 1996) that were characterized by durations less than 1 ms. These short-duration flashes were recorded in cells where high (50 dBz) reflectivity reached high altitude (8 km above mean sea level) and vertical updraft velocity exceeded 10 m/s. We speculate that some of the isolated short-duration discharges reported from VHF lightning mapping studies and reviewed above might be attempted cloud-to-ground leaders considered in this study.

Table 1. Characterization of Electric Field Records Acquired During Eight Thunderstorms in Gainesville, Florida, in 2006

<table>
<thead>
<tr>
<th>Storm ID, mm/dd/yy</th>
<th>Number of Records</th>
<th>Number of Attempted Leaders</th>
<th>Sampling Interval, ns</th>
<th>Record Length, ms</th>
<th>Pretrigger/Posttrigger, ms/ms</th>
<th>Number of Attempted Leaders for Different Pretrigger/Posttrigger Settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>05/24/06</td>
<td>1073</td>
<td>25 (2.3)</td>
<td>10</td>
<td>200</td>
<td>80/120</td>
<td>25 (76)</td>
</tr>
<tr>
<td>05/28/06</td>
<td>287</td>
<td>1 (0.4)</td>
<td>4</td>
<td>96</td>
<td>40/56</td>
<td>4 (12)</td>
</tr>
<tr>
<td>06/01/06</td>
<td>21</td>
<td>0 (0)</td>
<td>4</td>
<td>96</td>
<td>40/56</td>
<td>4 (12)</td>
</tr>
<tr>
<td>06/02/06</td>
<td>234</td>
<td>0 (0)</td>
<td>4</td>
<td>96</td>
<td>40/56</td>
<td>4 (12)</td>
</tr>
<tr>
<td>06/03/06</td>
<td>260</td>
<td>3 (1.2)</td>
<td>4</td>
<td>96</td>
<td>40/56</td>
<td>4 (12)</td>
</tr>
<tr>
<td>07/15/06</td>
<td>27</td>
<td>0 (0)</td>
<td>10</td>
<td>200</td>
<td>120/80</td>
<td>4 (12)</td>
</tr>
<tr>
<td>07/16/06</td>
<td>2</td>
<td>0 (0)</td>
<td>10</td>
<td>200</td>
<td>120/80</td>
<td>4 (12)</td>
</tr>
<tr>
<td>07/17/06</td>
<td>571</td>
<td>4 (0.7)</td>
<td>10</td>
<td>200</td>
<td>120/80</td>
<td>4 (12)</td>
</tr>
<tr>
<td>All data combined</td>
<td>2475</td>
<td>33 (1.3)</td>
<td>4 or 10</td>
<td>96 or 200</td>
<td>40/56, 120/80 or 80/120</td>
<td>33 (100)</td>
</tr>
</tbody>
</table>

*Percentages are given in parentheses.

Figure 6a. Electric field record illustrating definition of overall preliminary breakdown pulse train duration (T_{PB}) of an attempted leader.
Preliminary breakdown pulse trains of attempted negative cloud-to-ground leaders examined here typically contained two types of pulses, larger “classical” pulses with durations of the order of tens of microseconds (see Figure 7a) and “narrow” pulses whose durations were as short as a few microseconds, with many being in the 1 to 2 µs range (see Figure 7b). Smaller and narrower pulses tended to occur at the onset and toward the end of each pulse train. With our time resolution (sampling interval of 4 or 10 ns) we could detect submicrosecond-scale pulses in attempted leaders, but did not find any. (Note, however, that we have observed submicrosecond-scale pulses in “normal” preliminary breakdown pulse trains of negative cloud-to-ground flashes and in field waveforms of cloud discharges.) To the best of our knowledge, preliminary breakdown pulses with durations of the order of a few microseconds have never been reported before (probably due to insufficient time resolution), although Gurevich et al. [2003] and Rakov [2006] reported submicrosecond-scale pulses in cloud discharges.

A total of 35 preliminary breakdown pulse trains were found in 33 electric field records of attempted leaders, that is, there were two records each containing two distinct pulse trains. A histogram of the total pulse train duration (TPB) is shown in Figure 8a. The range of variation and arithmetic mean of total durations of pulse trains are 0.8–7.9 ms and 2.7 ms, respectively. Almost three quarters (74%) of the pulse trains were found to have total durations less than or equal to 3 ms. Figures 8b and 8c show ranges of variation (vertical bars) of pulse duration (TPW) and interpulse interval (TIP) in individual pulse trains, respectively. Almost half (46%) of the pulse trains were found to have minimum pulse durations in the range of 1–2 µs (see Figure 8b). The range of variation and the weighted (by number of pulses in the train) arithmetic mean of pulse durations for all 35 pulse trains were found to be 1–91 µs and 17 µs, respectively. For interpulse intervals (see Figure 8c) the range of variation and weighted (by number of interpulse intervals in the train) arithmetic mean are 1–530 µs and 73 µs, respectively.

As noted in section 1, only 18% (59 out of 327) of the electric field records of cloud-to-ground discharges in our auxiliary data set were found to have pronounced preliminary breakdown pulse trains. Assuming that all cloud-to-ground discharges are preceded by some kind of preliminary breakdown, we can use this percentage as a measure of detection efficiency of our system for preliminary breakdown pulse trains. Similar detection efficiency can be expected for preliminary breakdown pulse trains of our attempted leaders. If so, then the 35 attempted leaders identified in this study correspond to 18% of the total number of attempted leaders (both exhibiting and not exhibiting detectable preliminary breakdown pulse trains). Applying a correction factor to account for the 18% detection efficiency, we estimate the expected number of attempted leaders in our data to be about 194, which is about 8% of the total number of records (cloud and ground discharges combined). The relatively low percentage (less than 20%) of cloud-to-ground discharges exhibiting pronounced preliminary breakdown pulse trains is likely to be due to local noise at the field measuring site and relatively low (8 bit) amplitude resolution of our records. Indeed, a considerably larger percentage of ground flashes showing preliminary breakdown pulse trains was reported by Schulz and Diendorfer [2006] who used 12-bit digitizers and 12-bit resolution.

| Classification of Data According to Pulse Activity (or Lack of Such) Following the Preliminary Breakdown (PB) Pulse Train and Presence (or Absence) of Static Ramp |
|-----------------|-----------------|-----------------|
| Type            | Static Ramp     | Number of Events |
| PB pulse train followed by no pulse activity | without static ramp (Figure 2) | 7 |
| PB pulse train followed by nonreturn stroke–type pulses | with static ramp (Figure 5) | 4 |
performed electric field measurements at a specially selected very low noise site in Austria. In their data set, 89% of 92 negative multiple-stroke flashes and 71% of 94 negative single-stroke flashes (all recorded at distances ranging from 50 to 100 km) had detectable preliminary breakdown pulse trains. On the other hand, one cannot rule out regional, seasonal, or storm-type peculiarities in the relative size of preliminary breakdown pulses.

[27] We now discuss implications of our findings for lightning locating systems such as the U.S. National Lightning Detection Network (NLDN). Since the preliminary breakdown–type pulses considered here have the same polarity as return stroke pulses in negative cloud-to-ground flashes and durations of the initial half cycle of these two types of pulses may be comparable (a few tens of microseconds), some of the attempted cloud-to-ground leaders can be misclassified by the NLDN as low-intensity negative cloud-to-ground discharges. If we assume that about 25% of the 2475 records examined here were due to negative cloud-to-ground flashes, and that 25% of these cloud-to-ground flashes had peak currents equal to or less than 10 kA, the expected number of low-intensity (≤ 10 kA) negative cloud-to-ground events would be 155. If the NLDN recorded all these 155 negative cloud-to-ground events plus all 35 attempted leaders (all assumed to have NLDN intensities ≤ 10 kA), about 18% of reported low-intensity cloud-to-ground flashes would be misclassified events.

[28] The question remains if the largest preliminary breakdown pulse amplitudes are on average comparable to those of return stroke pulses. In our auxiliary data set the arithmetic mean of the ratio of the initial peak of the largest preliminary breakdown pulse to that of the corresponding first return stroke pulse is approximately equal to 0.6 (only for 18% of the events for which the preliminary breakdown was detectable). In 19% of the flashes, the largest preliminary breakdown pulse peak was greater than the corresponding first return stroke pulse peak. Schulz and Diendorfer [2006] reported that 7 (about 8%) of 92 negative multiple-stroke flashes and 6 (6%) of 94 negative single-stroke flashes in Austria had at least one preliminary breakdown pulse exceeding in amplitude the first return stroke pulse.

[29] In 2002–2003, the NLDN underwent its most recent system-wide upgrade [Cummins et al., 2006]. In the course of this upgrade, the original time-of-arrival LPATS sensors and early IMPACT sensors were replaced by more sensitive IMPACT-ESP sensors. Because of the higher sensor sensitivity coupled with modifications of waveform discrimination criteria, the upgraded NLDN is capable of recording low-intensity signals produced by cloud discharges. However, some of these cloud discharges are misclassified as low-intensity cloud-to-ground discharges, causing contamination of the lower-intensity end of the spectrum of cloud-to-ground discharges (both positive and negative) by cloud events. Although the pulse trains considered here are rare (less than 1.5% of the examined 2475 Florida electric field records), they might contribute significantly to the lower-intensity contamination of the NLDN output for negative flashes.

[30] Biagi et al. [2006] and Cummins et al. [2006] conducted single-station video observations of thunderstorms...
storms in Arizona, Texas-Oklahoma, and Colorado-Kansas-Nebraska and examined corresponding NLDN records to see if NLDN events labeled as negative cloud-to-ground discharges having peak currents less than or equal to 10 kA are associated with visible channels to ground. NLDN-reported negative cloud-to-ground discharges that were not confirmed by video observations of channels to ground constituted 48% (38 of 80) in Arizona, 58% (14 of 24) in Texas-Oklahoma, and “a majority” in Colorado-Kansas-Nebraska. Note that “nonconfirmed” events used in computing the percentages given above include the cases when there was no luminosity at all detected in association with the NLDN-reported negative cloud-to-ground discharges. There is a chance that some of the “no-luminosity” NLDN events were associated with an obscured or out-of-field-of-view channel to ground, in which case the above percentages should be viewed as upper bounds. [31] Johnson and Mansell [2006] used three-dimensional lightning channel mapping observations in Oklahoma as ground truth data to identify cloud and cloud-to-ground

![Figure 8b](image.png)

**Figure 8b.** Ranges of variation (vertical bars) and mean values (diamonds) of pulse duration ($T_{PW}$) in individual preliminary breakdown pulse trains. See also caption of Figure 8a.

![Figure 8c](image.png)

**Figure 8c.** Ranges of variation (vertical bars) and mean values (diamonds) of interpulse interval ($T_{IP}$) in individual preliminary breakdown pulse trains. See also caption of Figure 8a.
discharges. They examined negative NLDN events with reported signal strengths (intensities) less than 15 kA and found that 93% of them (27 of 29) could not be confirmed (by the “correct charge structure” and sometimes by existence of channel to ground) as negative cloud-to-ground discharges.

In summary, 48 to 93% of events reported by the NLDN as negative cloud-to-ground discharges with NLDN intensities less than or equal to 10 kA or less than 15 kA could not be confirmed by optical records or by three-dimensional lightning channel mapping observations. It is likely that many of these nonconfirmed negative cloud-to-ground events were misclassified cloud discharges.

Schulz and Diendorfer [2006] used independent continuous electric field records to evaluate responses of the Austrian lightning locating system (ALDIS), which is similar to the NLDN, to negative single- and multiple-stroke flashes. Of 92 multiple-stroke flashes, 40 (43%) were not detected correctly. (Note that the percentage of flashes “not detected correctly” was significantly higher than percentage of flashes not detected at all.) In 7 cases, preliminary breakdown pulses were accepted by ALDIS as first return strokes in cases other nonreturn stroke—type bipolar pulses were accepted as either first (6 cases) or subsequent (12 cases) return strokes. Of 128 single-stroke flashes, 34 (29%) were not detected correctly, with 9 and 16 ALDIS-reported return strokes being actually preliminary breakdown and other nonreturn stroke—type pulses, respectively.

Cummins et al. [2006] stated that “the current IC: CG classification methods in the NLDN need to be improved, and more sophisticated methods are being examined by Vaisala. Vaisala also plans to add an “ambiguous” category for events that cannot be clearly identified as “cloud” or “cloud-to-ground” pulses.”

5. Summary

Lightning events exhibiting pulse trains that are characteristic of preliminary breakdown in negative cloud-to-ground discharges, but are not followed by return stroke waveforms, are assumed to be manifestations of attempted cloud-to-ground leaders. A total of 2475 electric field records of lightning events that we acquired (using a sampling interval of 4 or 10 ns) in Gainesville, Florida, in 2006 were examined, and 35 waveforms in 33 of these records were found to satisfy the criteria (which are the characteristic features of preliminary breakdown pulse trains in negative cloud-to-ground flashes) set for attempted cloud-to-ground leaders.

Preliminary breakdown pulse trains of attempted cloud-to-ground leaders typically contained two types of pulses, larger “classical” pulses with durations of the order of tens of microseconds and “narrow” pulses whose durations were a few microseconds, with many being in the 1 to 2 μs range. Almost half (46%) of the pulse trains were found to have minimum pulse durations in the range of 1–2 μs. Smaller and narrower pulses tended to occur at the onset and toward the end of each pulse train. In addition to bipolar pulses with positive (atmospheric electricity sign convention) initial half-cycle, negative unipolar and negative (initial half-cycle) bipolar pulses were sometimes seen toward the end of the train. Characteristics of preliminary breakdown pulse trains in attempted leaders can be summarized as follows: (1) The range of variation and arithmetic mean of total durations of pulse trains are 0.8–7.9 ms and 2.7 ms, respectively, with 74% of the pulse trains having total durations less than or equal to 3 ms. (2) The range of variation and the weighted arithmetic mean of individual pulse durations are 1–91 μs and 17 μs, respectively. (3) The range of variation and the weighted arithmetic mean of interpulse intervals are 1–530 μs and 73 μs, respectively.

In our view, some of the isolated short-duration discharges which have been observed by Maier et al. [1996] and Kreibiel et al. [2003] who used VHF time-of-arrival lightning mapping systems and by Defe et al. [2001] who used a VHF interferometric lightning mapper, might be attempted cloud-to-ground leaders, similar to those considered in this study.

The preliminary breakdown—type pulses considered here have the same polarity as return stroke pulses in negative cloud-to-ground flashes and durations that may satisfy the U.S. National Lightning Detection Network (NLDN) criteria set for return strokes in negative cloud-to-ground flashes. As a result, some of the attempted cloud-to-ground leaders, which should belong to the cloud discharge category, can be misclassified by lightning locating systems, such as the NLDN, as negative cloud-to-ground discharges.

Acknowledgments

This research was supported in part by NSF grant ATM-0346164. The authors would like to thank W. Koshak and W. Schultz for providing additional information on their published data. Comments of three anonymous reviewers are appreciated.

References


Kitagawa, N. (1957), On the electric field change due to the leader channel to ground) as negative cloud-to-ground discharges.


Shao, X. M. (1993), The development and structure of lightning discharges observed by VHF radio interferometer, Ph. D. dissertation, New Mexico Inst. of Mines and Technol., Socorro, N. M.


A. Nag and V. A. Rakov, Department of Electrical and Computer Engineering, University of Florida, P.O. Box 116130, Gainesville, FL 32611-6130, USA. (amitabh@ufl.edu; rakov@ece.ufl.edu)