Preliminary Breakdown Pulse Trains in Electric Field Records of Negative Cloud-to-Ground Lightning

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ABSTRACT: In this study, we characterized the preliminary breakdown (PB) pulse trains in negative cloud-to-ground lightning. The data were acquired at the Lightning Observatory in Gainesville (LOG), Florida, in 2013. Distances to lightning channels ranged from 21 to 118 km. For 104 flashes, the geometric mean (GM) PB pulse train duration is 2.1 ms. The GM interval between the beginning of PB pulses train and first return stroke pulse onset (T_{PB-RS}) is 20 ms. The GM ratio of the largest PB pulse peak to the first return stroke pulse peak is 0.2. In our dataset, we found 9 flashes with very short (≤6 ms) T_{PB-RS}, which appears to be due to very high stepped leader speed. The GM NLDN-reported peak current of the first return stroke in these flashes is as high as 131 kA. We also examined the effect of noise on detectability of PB pulse trains. We found that 29% of 221 flashes had detectable PB pulses, and that after filtering the percentage increased to 47%. The percentage of flashes with detectable PB pulse trains varied significantly from one storm to another, from 13% to 100% before filtering and from 20% to 100% after filtering. Additionally, we examined the PB detectability as a function of distance and the first return stroke peak current.

1. INTRODUCTION

Preliminary breakdown (PB) is thought to be an intra-cloud process that initiates or leads to the initiation of the stepped leader [e.g., Rakov and Uman, 2003]. PB process is usually identified in electric field records by a bipolar pulse train with the typical duration of a few milliseconds [e.g., Clarence and Malan, 1957]. In negative cloud-to-ground lightning, the polarity of the initial half cycle of PB pulses is apparently always the same as the polarity of the following return stroke pulse. The time interval between the preliminary breakdown and the first return stroke can be viewed as stepped-leader duration. Based on electric field records of winter lightning in Albany, NY, Brook [1992] reported flashes with intense preliminary breakdown pulses and <4 ms leader durations (mean value was 2.75 ms vs. 8 ms in summer lightning). He attributed the observed differences to the different precipitation mixes in summer and winter thunderstorms.

In most cases, the amplitudes of preliminary breakdown pulses is smaller than that of the following return strokes. However, it was observed that the field peaks of some PB pulses can be comparable or even exceed that of the following return strokes [Brook, 1992; Nag and Rakov, 2009a].

Gomes et al. [1998], using the same instrumentation to record electric fields in Sweden and Sri

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Lanka, reported that 100% of 41 flashes in Sweden had detectable PB pulses, while only 19% of 47 flashes in Sri Lanka did so. Nag and Rakov [2009b] examined electric field records of negative cloud-to-ground flashes acquired in Gainesville, Florida, in 2006 and found that 18% of them had detectable PB pulse trains. By comparing the percentages of flashes with detectable PB pulse trains in different regions, they found that a larger percentage of flashes exhibited detectable PB pulse trains at higher latitudes than at lower latitudes. They attributed this observation to the more frequent presence of a significant lower positive charge region (LPCR) at higher latitudes than at lower ones. In contrast, Baharudin et al. [2012] found that 97% of 100 flashes recorded in Malaysia (low-latitude location) and 100% of 100 flashes recorded in Florida (relatively low-latitude location) had detectable PB pulses. Also, Strolzenburg et al. [2013] reported that 100% of 127 flashes in Florida had PB pulses. It appears that there are additional factors that can influence the percentage of flashes with detectable PB pulses.

In this paper, we will (1) characterize PB pulse trains in negative cloud-to-ground flashes (CGs) by using newly acquired Florida data, (2) present 9 flashes with very short leaders and show that they are characterized by very high peak currents of the first return stroke and very high leader speeds, and (3) examine four factors that can affect the detectability of PB pulses, including signal/noise ratio, type of storm, distance, and first return stroke peak current.

2. DATA

The dataset used in this study was acquired at the Lightning Observatory in Gainesville (LOG), Florida [Rakov et al., 2014] by using two-station (LOG-Golf Course site) triggering scheme. The Golf Course site (GC) is located about 43 km from LOG. When electric field exceeds the preset threshold at GC (empirically selected to record primarily CGs within a few tens of kilometers of GC), the instrumentation at GC is triggered and a trigger pulse is sent to LOG over the Internet by using an IP-addressed digital input and output device. The total number of flashes recorded at LOG was 221, 204 of which were reported by the NLDN. According to the NLDN, distances between the recorded flashes and LOG ranged from 21 to 118 km with over 85% of the flashes being in the 20-60 km range.

The electric field measuring system includes a circular flat-plate antenna followed by a unity gain, high input impedance amplifier with an active integrator. The system has a useful frequency bandwidth of 16 Hz to 15 MHz. The decay time constant is 10 ms. The vertical resolution is 8-bit and the sampling interval is 20 ns. The record length is 2 s. Pretrigger time (time interval between the beginning of the record and the first RS) was not fixed because of the IP triggering scheme. The minimum and maximum pretrigger times were 50 ms and 1878 ms, respectively. The average pretrigger time was 556 ms and over 95% of records had >100 ms pretrigger times. The waveforms were smoothed by using a 50-points (1-μs) moving time-averaging window. In the following, we refer to this smoothing process as filtering. After filtering, 104 (47%) of 221 flashes were found to have detectable PB pulse trains. VHF lightning channel images obtained using the eight-station Lightning Mapping Array (LMA) operating in Florida (with one of the stations located at GC) were examined for selected events.

3. RESULTS AND DISCUSSION

Characterization of PB pulse trains

Characteristics of PB pulse trains for 104 flashes are examined here. They include PB pulse train duration, PB-RS interval, and PB/RS field peak ratio, where RS stands for return-stroke pulse. Number of pulses in the train and characteristics of individual PB pulses are outside the scope of this study.

1) PB Pulse Train Duration

The histogram of PB pulse train duration is shown in Figure 1. The arithmetic mean and geometric mean of the PB pulse train duration are 3.6 ms and 2.1 ms, respectively, which are close to the 3.4 ms and 3.2 ms previously reported for negative lightning in Florida by Nag and Rakov [2009a].

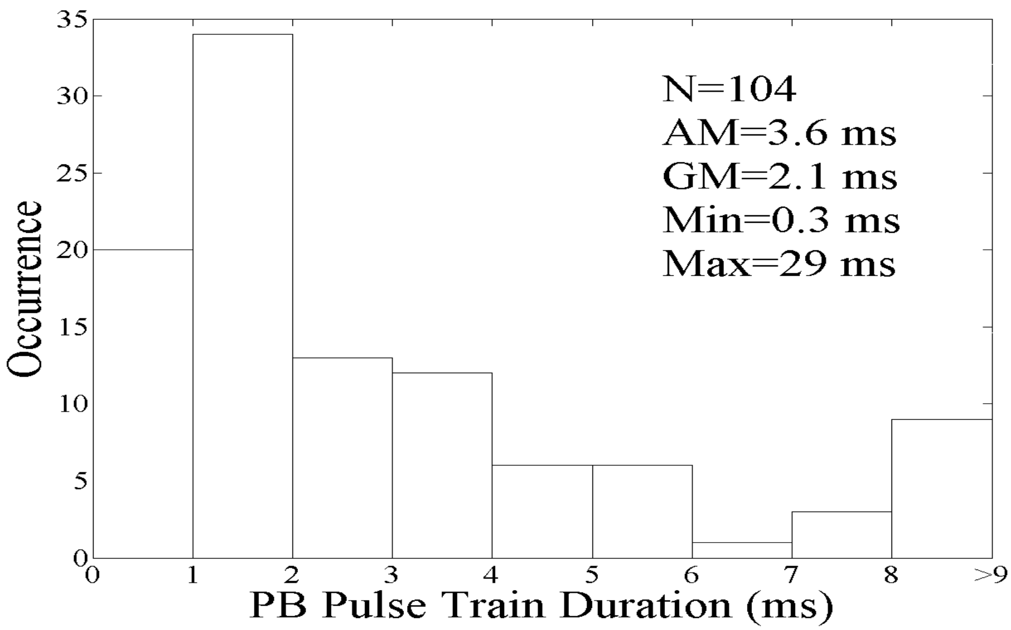

Figure 1. Histogram of PB pulse train duration.

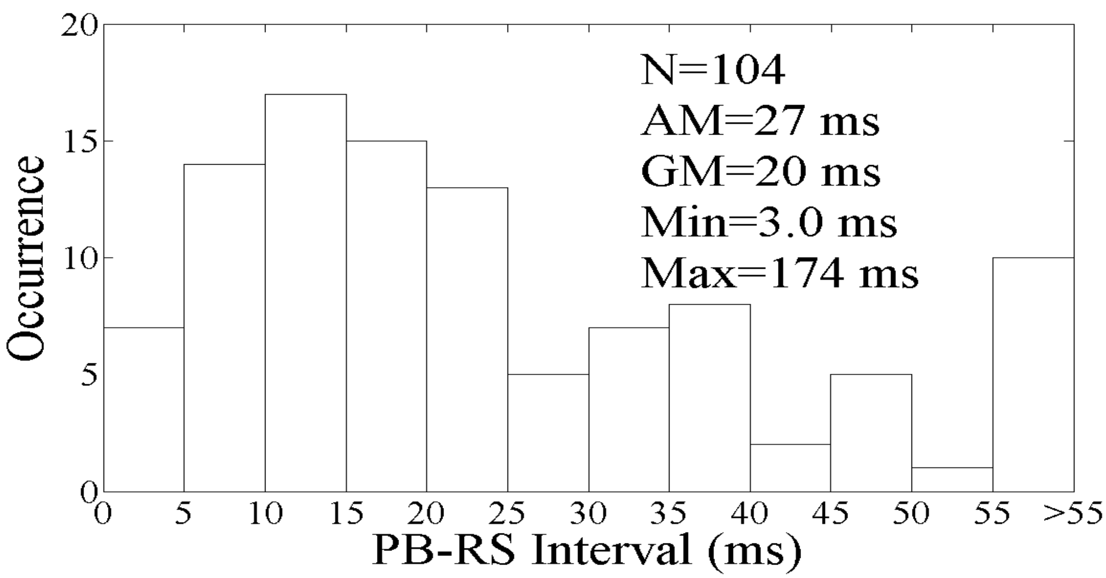

Figure 2. Histogram of PB-RS interval.

2) PB-RS Interval

The histogram of PB-RS interval is shown in Figure 2. The arithmetic mean and geometric mean of PB-RS interval are 27 ms and 20 ms, respectively, which are close to 22 ms and 17.7 ms previously reported for Florida negative lightning by Baharudin et al. [2012].

3) PB/RS Field Peak Ratio

For 93 of 104 flashes (excluding 11 saturated records), the ratio of the largest PB pulse peak to the first return stroke pulse peak ranges from 0.05 to 0.97 (see Figure 3), with the arithmetic mean and geometric mean of 0.26 and 0.20, respectively.

In our study, only 5 (5%) of 93 flashes had the largest PB pulse peak exceeding half of the peak of the following return-stroke pulse, and no PB pulse peak exceeded the following return-stroke pulse peak. This is a considerably lower occurrence of large PB pulses than in the previous studies by Nag and Rakov [2009a] and Baharudin et al. [2012]. The disparity might be, at least in part, due to the exclusion of saturated events in our study, which tend to have more intense PB pulses. As a result, our average PB/RS ratio should be considered as a lower boundary.

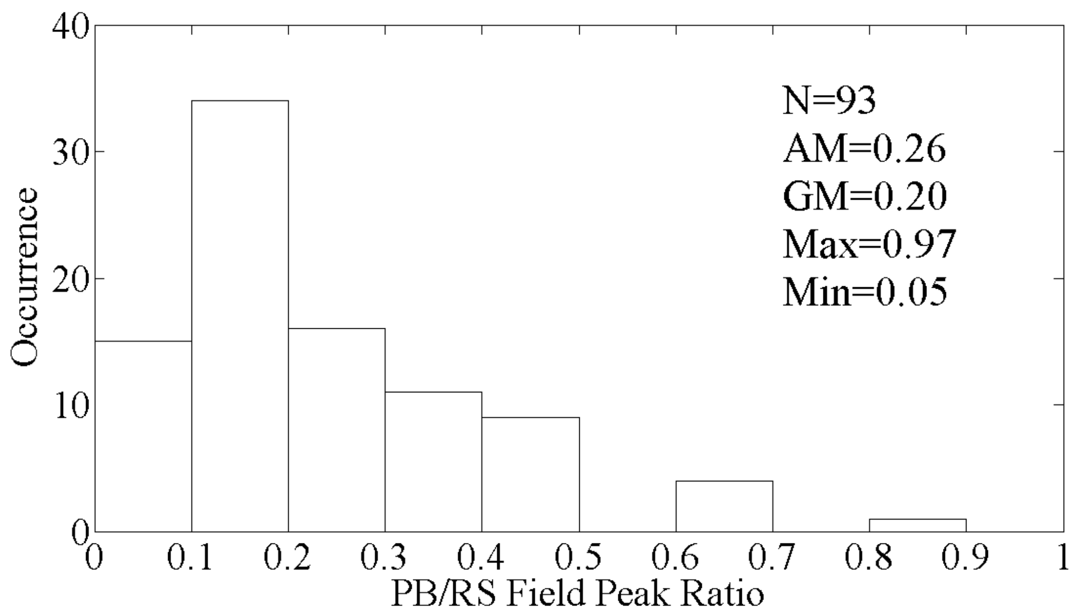

Figure 3. Histogram of PB/RS field peak ratio.

Very Short PB-RS Interval Flashes

We observed that 9 (9%) of 104 flashes had very short (≤6 ms) PB-RS intervals. These 9 flashes are listed in Table 1. For 8 of them, the peak current of the first return stroke reported by the NLDN exceeded 100 kA, and for the remaining one the peak current was 82 kA, still a factor 2 to 3 higher than typical first RS peak currents. For these 9 events, the GM of T_{PB-RS} is 4.5 ms, which is about a factor of 8 shorter than the typical negative stepped leader duration of 35 ms [Rakov and Uman, 2003] and more than 4 times shorter than the GM PB-RS interval in all our 104 flashes. Further, the GM of first return stroke peak current for the 9 flashes is 131 kA, which is a factor of 4-5 larger than typical (median) value of 30 kA [Rakov and Uman, 2003]. Such short time intervals between PB and RS can be due to a very fast stepped leader or very low height at which the leader initiated, or both. We estimated the leader initiation height by using the altitude of the first Lightning Mapping Array (LMA) VHF source for 5 of the 9 very short PB-RS interval events (no LMA data are available for the remaining 4 events). The altitudes of the first LMA sources range from 4.56 to 5.86 km (mean is 5.15 km). We also randomly selected 8 events with normal $T_{PB\text{-}RS}$ (mean is 23 ms) from our dataset and found the altitudes of the first LMA source ranging from 4.79 to 5.96 km (mean is 5.34 km). It appears that the initiation heights for very short $T_{PB\text{-}RS}$ events are more or less the same as those for events with normal $T_{PB\text{-}RS}$, which implies very high leader speeds for the very short $T_{PB\text{-}RS}$ events. Estimated leader speeds (lower bounds) are given in Table 1. They are of the order of 10^6 m/s, while typical stepped leader speeds are of the order of 10^5 m/s [e.g., Rakov and Uman, 2003].

Table 1. Summary of Short PB-RS Interval Events

Flash ID	Time Interval between PB and First Return Stroke (ms)	First Return Stroke Peak Current Reported by NLDN (kA)	Inferred Leader Speed* (m/s)
839	3.5	222	1.61×10^6
854	4.5	133	1.3×10^6
881	5.9	82	0.78×10^6
882	6.0	102	-
1138	4.4	129	-
1203	4.0	150	1.23×10^6
1204	3.6	172	1.28×10^6
1205	4.3	110	-
1215	5.0	128	-
GM	4.5	131	1.21×10^6

* Estimated as $v=H/T_{PB\text{-}RS}$, where H is the altitude of the first LMA source. This estimate should be considered as a lower bound because the actual (3D) channel length should be considerably larger than H.

Factors that can affect PB detectability

1) *Signal/Noise Ratio of Recording System*

By using the criteria for identifying PB pulse trains adopted by Nag and Rakov [2009a], we found that 29% of 221 negative cloud-to-ground flashes have detectable preliminary breakdown pulses in raw field records. However, after applying moving-average filtering, the percentage increased to 47%. This means the detectability of preliminary breakdown pulses is significantly affected by the signal/noise ratio of the recording system. If the noise level is too high, less intense PB pulse trains will be not be detected. Examples of waveforms before and after filtering are shown in Figure 4. Vertical resolution of the recording system is also a factor, but it is not examined here.

2) *Type of Storm*

The 221 flashes are sorted by individual storms in Table 2. The total number of storms with at least 4 recorded flashes was 12. For each storm, the corresponding percentage of flashes with detectable PB pulse trains is given. It can be seen that regardless of filtering, the percentage of flashes with detectable PB pulse train significantly varies from one storm to another. For example, the storm that occurred on 08/23/2013 (a total of 90 CGs) had only 13% and 29 % of flashes with detected PB pulse trains before and after filtering, respectively. However, for some other storms, over 80% of flashes (after filtering) exhibited detectable PB pulse trains. Thus, the detectability appears to be affected by the type of storm. Based on the hypothesis of Nag and Rakov [2009b] that PB pulses are the manifestation of the interaction of stepped-leader-like process with the lower positive charge region (LPCR) in the cloud, we speculate that storms with a higher percentage flashes with detectable PB pulse trains should have a more significant LPCR.

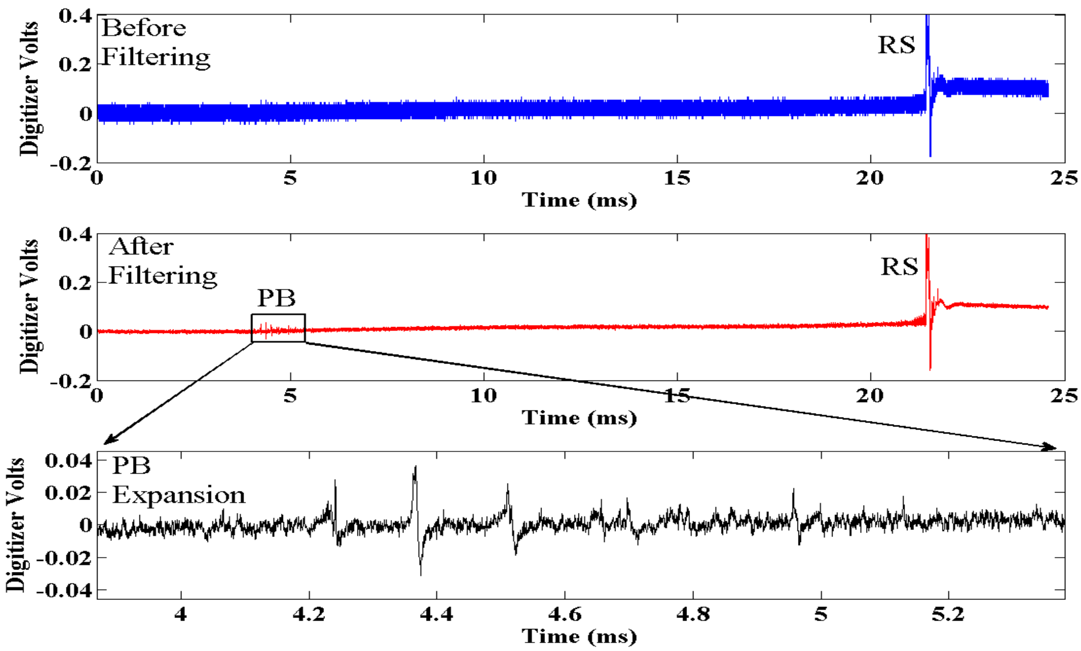

Figure 4. Comparison of electric field waveforms before and after filtering. The top panel shows the raw record (before filtering) in which no PB pulses are seen. However, in the middle panel, showing the same record after filtering, one can clearly see a PB pulse train around 5 ms. The bottom panel shows the PB pulse train (after filtering) on an expanded time scale.

Table 2. Percentage of Flashes with Detectable PB Pulse Trains Before and After Filtering

Storm ID (mm/dd/yy)	Number of Flashes Recorded	Percentage of Flashes with Detectable PB Pulses	
		Before filtering	After filtering
07/19/2013	4	75%	75%
07/22/2013	5	20%	20%
08/01/2013	7	71%	71%
08/15/2013	9	22%	56%

Storm ID (mm/dd/yy)	Number of Flashes Recorded	Percentage of Flashes with Detectable PB Pulses	
		Before filtering	After filtering
08/17/2013	25	20%	48%
08/18/2013	5	80%	80%
08/21/2013	4	75%	100%
08/22/2013	17	47%	71%
08/23/2013	7	71%	86%
08/30/2013	90	13%	29%
08/31/2013	8	38%	75%
09/06/2013	18	41%	61%
Storms with < 4 recoded flashes	22	23%	41%
Total	221	29%	47%

3) Distance to the Lightning Channel

We now examine the effect of distance between the observation point and the lightning channel on detectability of PB pulse trains. The percentage of flashes with detectable PB pulse trains as a function of NLDN-reported distance is given in Table 3. Note that the number of NLDN-reported flashes (204) is less than the total number of flashes (221) in our dataset. For the range of 20-30 km, the PB pulse train detectability is 100%. For the range of 30-40 km, the detectability drops to 65%, and it further drops to 41% in the 40-50 km range. From the data for the 20-50 km range, it appears that PB detectability decreases as the distance increases, but it does increase in the 50-70 km range. Further work is needed to clarify how exactly the PB pulse detectability depends on distance.

Table 3. Percentage of Flashes with Detectable PB Pulse Trains in Different Distance Ranges

Distance range (km)	Number of Flashes	Number of Flashes with Detectable PB	Percentage of Flashes with Detectable PB
20-30	7	7	100%
30-40	23	15	65%
40-50	111	45	41%
50-60	40	21	53%
60-70	6	4	67%
70-80	3	0	0%
80-90	5	2	40%
90-100	6	2	33%
100-110	2	0	0%
110-120	1	1	1%
Total	204	97	48%

4) Peak Current

We found (for the first time) that flashes with higher first return stroke peak currents are more likely to have detectable PB pulse trains. Figure 5 shows PB pulse detectability as function of the first return stroke peak current reported by the NLDN. One can clearly see that for flashes with first return stroke peak current less than 60 kA, the detectability is less than 50% (minimum is 38% in the 20-40 kA range). However, for the 60-240 kA range, the detectability is appreciably higher (maximum is 91% in the 80-100 kA range). It appears that flashes with higher return stroke peak currents tend to have more intense PB pulses, so that they are more likely to be detected.

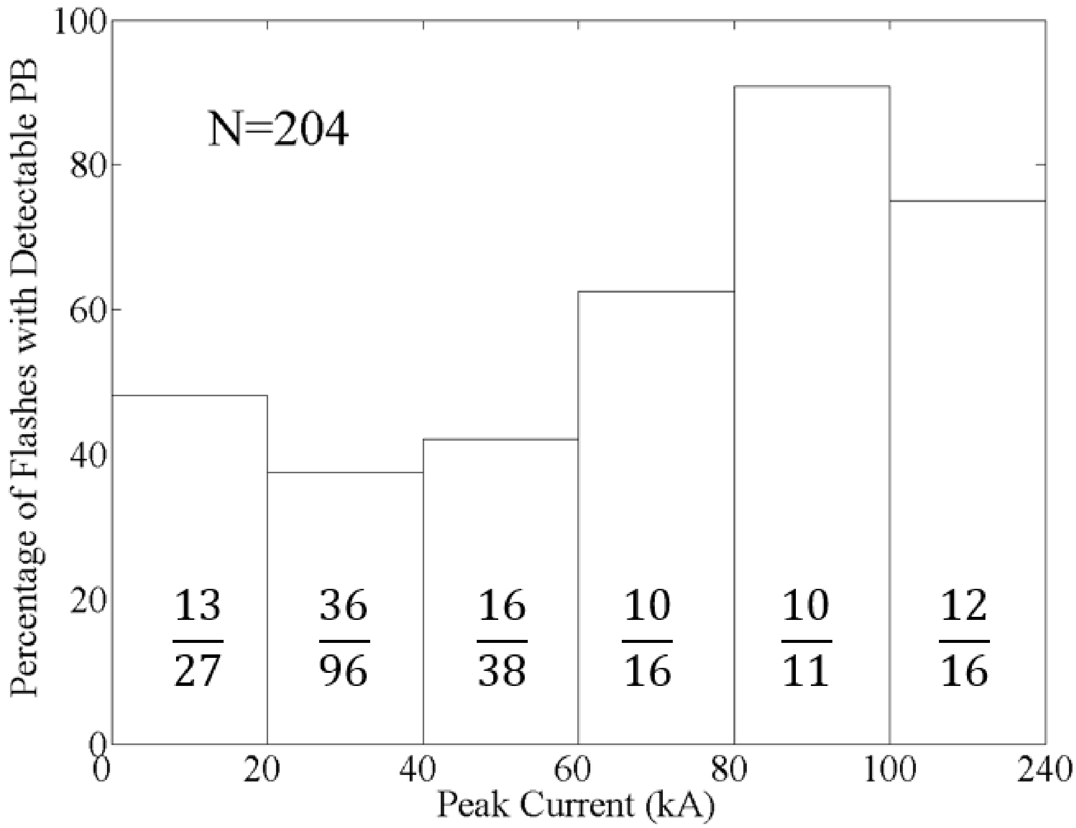

Figure 5. Percentages of flashes with detectable PB pulse trains for different ranges of first return stroke peak current. The ratio given inside each column indicates the number of flashes with detectable PB pulse trains (numerator) and the total number of flashes with NLDN reported currents (denominator).

SUMMARY

In the dataset of 221 negative cloud-to-ground flashes acquired in Florida, we found that 29% of them had detectable PB pulse trains in raw wideband electric field records and 47% in the same records after they were smoothed to increase the signal/noise ratio. Detectability of PB pulse trains apparently depends on the type of thunderstorm, since the percentage of flashes with detectable PB pulses varies significantly from one storm to another. Distance can potentially be another influencing factor, but we did not observe a clear trend in the 40-120 km range. Further investigation is needed. We found that the flashes with higher first return stroke peak currents are more likely to have detectable PB pulses.

Characteristics of PB pulse trains of 104 negative CG flashes were examined. The GM PB pulse train duration is 2.1 ms. The GM interval between the beginning of PB pulses train and first return stroke pulse onset ($T_{PB\text{-}RS}$) is 20 ms. The GM ratio of the largest PB pulse peak to the first return stroke pulse peak is 0.2. All the characteristics of PB pulse trains presented in this paper are generally consistent with those reported from previous studies (except for the PB/RS field peak ratio). Flashes with very short PB-RS intervals have very high first RS peak currents and very high stepped leader speeds.

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