Characterization of Negative Cloud-to-Ground Lightning in Florida

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Abstract

We examined characteristics of negative cloud-to-ground lightning flashes using their electric field waveforms acquired at the Lightning Observatory in Gainesville (LOG), Florida in the summers of 2013 and 2014. Flash multiplicity, interstroke interval, flash duration, and first to subsequent stroke field peak ratio are determined for 478 flashes containing 2188 strokes and compared with previous results obtained in Florida and in other regions. We found that the average number of strokes per flash is 4.6 and the percentage of single-stroke flash is 12%. The geometric means of interstroke interval, flash duration, and first to subsequent stroke field peak ratio are 52 ms, 223 ms, and 2.4, respectively. About one-third (34%) of multiple-stroke flashes have at least one subsequent stroke whose field peak is greater than that of the first stroke. The geometric mean of normalized electric field peak shows a relatively weak tendency to decrease with increasing stroke order. We also found that the detectability of preliminary breakdown (PB) pulse train is affected by the signal/noise ratio, type of storm, peak current and distance. For 222 PB pulse trains, statistics on pulse duration, time interval between PB pulse train and return stroke (PB-RS interval), and PB to RS field peak ratio (PB/RS ratio) are presented. Very short PB-RS (≤6 ms) intervals were

observed to be associated with very high return-stroke peak currents and stepped-leader speeds.

1. Introduction

It is well know that lightning flash density and polarity dramatically vary with geographical location and season. However, it is still not certain if similar dependences exist for other lightning parameters. Clearly, lightning parameters can vary from one storm to another (Biagi et al. 2007; Saraiva et al., 2010), which may influence statistics, particularly in the case of small sample size. Before attributing any variation of lightning parameters to regional or meteorological peculiarities, one should rule out the influence of measuring and data processing techniques used in different locations, as well as methodology and limited sample size.

Many characteristics of negative cloud-to-ground lightning in Florida were studied by the University of Florida Lightning Research Group in the early 1990s (e.g., Rakov and Uman, 1990; Thottappillil et al., 1992; Rakov et al., 1994). For 76 negative flashes recorded during 3 storms in Florida in 1979, Rakov et al. (1994) examined the number of strokes per flash (multiplicity) and percentage of single-stroke flashes. They used electric field and optical data and found that the percentage of single-stroke flashes was 17% and the arithmetic mean flash multiplicity was 4.6. Thottappillil et al. (1992) found that 15 (33%) of 46 multiple-stroke flashes had one or more subsequent return strokes with distance-normalized initial electric field peak greater than that of the corresponding first return stroke, and that the interstroke interval preceding these greater-than-first subsequent strokes were more than 1.7 times longer than the average preceding interstroke interval for all subsequent strokes in their dataset.

Nag et al. (2008a) examined the ratio of electric field peaks of first and subsequent return strokes based on the data acquired in Florida, Austria, Brazil, and Sweden. They found that the electric field peak of first return strokes was on average 1.7 to 2.4 times larger than its counterpart for subsequent return strokes. For 239 negative subsequent strokes in Florida, the arithmetic and geometric means of first to subsequent return stroke field peak ratio were 2.1 and 1.7, respectively.

Nag and Rakov (2008b) examined electric field records of negative cloud-to-ground flashes acquired in Gainesville, Florida, in 2006 and found that 18% of them had detectable preliminary breakdown (PB) pulse trains. However, from more recent studies of PB pulse trains in negative lightning in Florida, Baharudin et al. (2012) and Marshall at al. (2014) found that 100% of flashes in each study had detectable PB pulse trains. Possible reasons for the discrepancy, including differences in noise level, record length, and distance, were discussed by Marshall et al. (2014).

In this paper, the characteristics of negative cloud-to-ground lightning in Florida will be revisited by analyzing electric field records of 478 flashes from 17 storms recorded in 2013 and 2014 at the Lightning Observatory in Gainesville (LOG), Florida. Flash multiplicity, interstroke interval, flash duration, first to subsequent return stroke field peak ratio, and percentage of flashes with detectable PB pulses will be examined. Further, we will discuss four factors that may affect the detectability of PB pulses: the signal/noise ratio of recording system, type of storm, distance between the observation point and lightning channel, and prospective return-stroke peak current reported by the U. S. National Lightning Detection Network (NLDN). Additionally, characteristics of PB pulse trains will be presented.

2. Experimental Setup and Data

The dataset of 478 negative cloud-to-ground flashes in this study was acquired at LOG by using the two-station (LOG-Golf Course site) trigger scheme. The Golf Course (GC) site is located in Starke, about 43 km from LOG. When the lightning-produced electric field at GC exceeds the preset threshold, the measuring instrumentation at GC is triggered, and a trigger pulse is sent to LOG over the Internet by using IP-addressed digital input and output (ipIO) devices as schematically illustrated in Fig. 1. Due to our use of this triggering scheme, the majority of lightning flashes recorded at LOG were relatively close to GC. The locations of first strokes of the 478 flashes reported by the NLDN along with the LOG and GC locations are shown in Fig. 2. The distances from LOG to lightning strike points were in the range of 16-330 km and the geometric mean distance was 55 km. Over 73% of the events were in the 20-60 km range.

The electric field measuring system at LOG includes an elevated circular flat-plate antenna followed by high-gain amplifier with an active integrator. The bandwidth of the system is 16 Hz to 10 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 triggering scheme. The pretrigger times were in the range of 46-1879 ms. The average pretrigger time was 612 ms and over 97% of records had >100 ms pretrigger times. Additional information about LOG is found in Rakov et al. (2014)

All the electric field waveforms analyzed in this study were smoothed (filtered) by using a 50-point (1-μs) moving time-average window in order to improve the signal/noise ratio. NLDN data were used to confirm that the first stroke of each flash was not missed by our system due to insufficient pretrigger time (assuming that first strokes are unlikely to be missed by the NLDN).

3. Characteristics of Negative Cloud-to-Ground Flashes in Florida

3.1 Multiplicity and Percentage of Single-Stroke Flashes

Out of 478 flashes containing 2188 strokes recorded during 17 storms, 57 (12%) were single-stroke flashes. The average number of strokes per flash was 4.6 and the geometric mean was 3.7. A histogram of multiplicity is shown in Fig. 3. In the previous study of Rakov et al. (1994), 76 flashes recorded during 3 storms on average had 4.6 strokes per flash, and the percentage of single-stroke flash was 17%. Our results are consistent with the previous findings. Information on multiplicity and percentage of single-stroke flashes in Florida and in other regions is summarized in Table 1, from which it follows that these two parameters are probably not significantly influenced by location.

3.2 Interstroke Interval and Flash Duration

Fig. 4 shows a histogram of the interstroke interval. The interstroke intervals were measured between the return-stroke field peaks. The arithmetic mean (AM) and geometric mean (GM) of all the interstroke intervals are 80 ms and 53 ms, respectively. Thottappillil et al. (1992) reported that GM of 199 interstroke intervals (46 flashes) was 57 ms. Rakov et al. (1994) reported that the GM of 270 interstroke intervals (76 flashes) was 60 ms. Our results are comparable with the corresponding values from the previous studies in Florida.

Fig. 5 shows a histogram of the flash duration for multiple-stroke flashes only. We define here the flash duration as the time interval between the electric field peaks of the first stroke and the last subsequent stroke. The GM duration for 421 multiple-stroke flashes is 223 ms, which is close to 216 ms and 229 ms, which are GM flash durations of negative cloud-to-ground flashes observed in Arizona and Sao Paulo, respectively (Saraiva et al., 2010). We are not aware of previous flash duration measurements in Florida.

Information on interstroke intervals and flash duration in Florida and in other regions is summarized in Table 2, from which no significant variation from one region to another is seen.

3.3 First to Subsequent Return Stroke Field Peak Ratio

Fig. 6 shows a histogram of the ratio of first to subsequent electric field peaks. For 1693 subsequent strokes (excluding saturated records), the ratio ranges from 0.3 to 28 with a GM of 2.4 and an AM of 3.1, which are somewhat higher than their counterparts reported for Florida and other regions by Nag et al. (2008a) (see Table 3). Higher ratios in this study are possibly a result of filtering, which allowed us to detect more smaller amplitude strokes (many of them had NLDN-reported currents below 10 kA). Out of 421 multiple-stroke flashes, 144 (34%) had at least one subsequent stroke whose field peak was greater than that of the first stroke, which is very close to 33% (15 of 46) reported by Thottappillil et al. (1992).

Shown in Fig. 7 are electric field peaks of subsequent strokes that are normalized to their corresponding first return stroke peaks and plotted versus stroke order. For strokes of order 2 to 10 (when sample sizes are greater than 20), the geometric mean of normalized electric field peak shows a relatively weak tendency to decrease with increasing stroke order. The range of variation of GM normalized electric field peak for strokes of order 2 to 15 is from 0.50 (stroke order 2) to 0.23 (stoke order 13).

3.4 Variation of Lightning Parameters from One Storm to Another

Statistics on flash multiplicity, interstroke interval, flash duration, and ratio of first to subsequent electric field peak for 17 individual storms are presented in Table 4. Some significant differences were observed. For instance, the average multiplicity for the storm on 09/06/2013 was 3.5 (N=17) while its counterpart for the storm on 08/02/2014 was 6.1 (N=24). The GM interstroke interval and GM flash duration for the storm on 05/15/2014 were 38 ms (N=48) and 128 ms (N=16), respectively, 2-4 times smaller than 71 ms (N=75) and 554 ms (N=14) for the storm on 07/05/2014. The average ratio of first to subsequent return stroke electric field peak for the storm on 07/25/2014 was 5.5 (N=61), 2.8 times larger than 2.2 for the storm on 06/08/2014 (N=114). However, the majority of storms had similar statistics for all the considered lightning parameters.

4. Factors Affecting Detectability of PB Pulse Trains

4.1 Signal/Noise Ratio of Recording System

The criteria for identifying the PB pulse trains described by Nag and Rakov (2008b) were used in this study. For the raw data, the percentage of flashes with PB pulse train was 22%. However, after applying moving-average filtering to the data, the percentage increased to 46%, which means that the signal/noise ratio significantly affects the detectability of PB pulse trains. Fig. 8 shows an example of records before and after filtering.

4.2 Type of Storm

The 478 flashes are grouped by storm in Table 5. For each storm, the percentage of flashes with detectable PB pulse train is given. It is clear from Table 5 that there is a significant variation of detectability from one storm to another, both before and after filtering. For example, before filtering, the storm on 07/03/2014 had only 6% of flashes with detectable PB pulse train, while this percentage for the storm on 07/10/2014 was 53%. After filtering, the percentages of flashes with detectable PB pulse train for these two storms increased to 28% and 100%, respectively, with the difference still being large.

Cooray and Jayaratne (2000) found that the PB pulses produced by lightning in Sweden were much more intense than those in Sri Lanka. They attributed the difference to stronger lower positive charge region in thunderstorms in Sweden. Based on the hypothesis proposed by Nag and Rakov (2009a) that PB pulses are the manifestation of interaction between a negative stepped leader and the lower positive charge region , we speculate that storms with higher percentage of flashes with detectable PB pulse train may have a more significant lower positive charge region. We also observed that flashes with detectable PB pulses tend to occur close to each other temporally (cluster in time), which might indicate that PB intensity depends cloud charge structure that changes during the storm life cycle.

4.3 Prospective Return-Stroke Peak Current

We found that flashes with higher first return stroke peak currents (only current magnitudes are considered here) are more likely to have detectable PB pulse train. The detectability of PB for all the 478 flashes is plotted versus first stroke peak current in Fig. 9a which shows a generally increasing trend. In order to reduce the effect of different distances to the LOG for different flashes, which will be examined in the next section, we chose 204 flashes in the relatively narrow 40-50 km distance range (which has the largest sample size compared to other ranges) to see the effect of the peak current more clearly. One can see from Fig. 9b that the PB pulse train detectability tends to increase with the increasing prospective peak current. If we combine some adjacent bins in Fig. 9b, the percentages of flashes with detectable PB pulse train will be 44% for the 0-40 kA range (N=133), 63% for the 40-80 kA range (N=59), and 92% for the >80 kA range (N=12). Thus, flashes with higher first return stroke peak currents are generally more likely to have detectable PB pulse trains, although this trend can be countered by the distance dependence (discussed in the next section). In other words, a less-intense event at a smaller distance can have the same probability of PB detection as a more distant event of higher intensity.

4.4 Distance from the Strike-Point Location to the Observation Point

The effect of distance from the strike-point location of flash to the observation point on detectability of PB pulse trains is examined in this section. The PB detectability for all the 478 flashes is plotted versus distance in Fig. 10a from which no clear dependence on distance can be seen, probably because of the effect of first-stroke peak current discussed in the previous section. In order to reduce that effect, we chose flashes with first-stroke peak currents in the relatively narrow 30-40 kA range (which has the largest sample size compared to other ranges) to examine the PB detectability variation versus distance. The results are shown in Fig. 10b. Although the sample size in the first two bins and the last several bins are rather small, similar to the analysis of the effect of prospective peak current on detectability of PB pulse trains, a decreasing trend is evident. If we combine some adjacent bins, we can find that the PB detectability for flashes in the distance ranges 10-30 km (N=6), 30-60km (N=80), and more than 60 km (N=21) are 83%, 46%, and 19%, respectively. Also, one can see from Fig. 2 that most flashes with detectable PB pulse train before filtering (black dots) are close to the LOG. Therefore, as expected, the detectability of PB pulse trains decreases significantly with increasing distance from the strike-point location to the observation point. However, this trend can be countered by a higher probability of recording larger-current events from larger distances, when measurements are performed at a single station with a fixed trigger threshold.

5. Characteristics of PB Pulse Trains

The statistics on PB pulse train duration, PB-RS time interval, and PB/RS field peak ratio for 222 flashes are summarized and compared to previous results for Florida negative cloud-to-ground lightning in Table 6.

The AM and GM of the PB pulse train duration are 2.2 ms and 1.7 ms, respectively, which are less than 3.4 ms and 3.2 ms previously reported for 12 unfiltered PB pulse trains by Nag and Rakov (2009b). One possible reason for the difference is that many less intense PB pulse trains identified after filtering had a small number of pulses, which lead to a shorter duration of PB pulse train. It is likely that there are even smaller PB pulses which are not detectable after filtering. Therefore, the PB pulse train duration in our study should be considered as a lower boundary.

The PB-RS interval is defined as the time interval between the peak of the first pulse of PB pulse train and the peak of return stroke. The PB-RS intervals for 222 flashes ranged from 2 ms to 156 ms with an AM of 24 ms and a GM of 19 ms, which are very close to 22 and 18 ms reported for 100 PB pulse trains by Baharudin et al.

(2012) and much less than 44 ms reported for 103 PB pulse train by Marshall et al. (2014).

The PB/RS ratio is defined as the ratio of the electric field peak of the largest PB pulse to that of the first return stroke. PB/RS ratios were determined for 214 flashes (excluding 8 events with saturated records). They ranged from 0.02 to 2.1 with an AM of 0.23 and a GM of 0.15, which are somewhat smaller than the 0.29 and 0.22 reported by Baharudin et al. (2012), and 2-3 time smaller than the 0.62 and 0.45 reported by Nag and Rakov (2009b). The factor of 2-3 difference is due to the fact that Nag and Rakov (2009b) did not use filtering and, hence, could not detect PB pulse trains with lower amplitudes.

Relation between the PB-RS interval and the peak current of first return stroke is examined and a scatterplot is shown in Fig. 11, We found that most flashes with first-stroke peak currents higher than 80 kA had PB-RS interval less than 20 ms, and all the flashes with PB-RS interval longer than 40 ms had peak currents lower than 60 kA. In our data set, 9 flashes were observed to have very short PB-RS time interval ($\leq$ 6 ms) and their average first stroke peak current is 114 kA. Zhu et al. (2014) previously reported that 9 flashes with average PB-RS interval of 4.5 ms had average first stroke peak current of 131 kA. By using available Lightning Mapping Array (LMA) data for 5 of the 9 flashes, they found that these flashes initiated at the normal height (average height was 5.15 km) and moved very fast (inferred average 1D leader speed is 1.2×10^6 m/s).

Wu et al. (2013) and Marshall et al. (2014) found that flashes with longer PB-RS intervals had weaker PB pulse trains and flashes with more intense PB pulse trains had shorter PB-RS intervals. The relation between the relative intensity of PB pulse train (PB/RS ratio) and PB-RS time interval, based on our data is shown in Fig. 12. There appears to be no clear trend. For 12 flashes with PB/RS>0.8, the average PB-RS interval is 38 ms, which is 1.6 times larger than the average PB-RS interval for all 214 flashes combined. In addition, the majority of flashes associated with shorter PB-RS intervals tend to have weaker PB pulse train.

6. Conclusions

The characteristics of negative cloud-to-ground lightning were examined by analyzing the electric field waveforms of 478 flashes recorded during 17 storms in Florida. The percentage of single-stroke flashes is 12% and the average flash multiplicity is 4.6. The arithmetic mean (AM) and geometric mean (GM) of interstroke intervals are 80 ms and 52 ms. The AM and GM of flash durations are 329 ms and 223 ms. The ratios of first to subsequent stroke field peaks for 1693 subsequent strokes range from 0.3 to 28 with an AM of 3.1 and a GM of 2.4. The GM normalized electric field peaks of subsequent strokes show a slowly descending trend with increasing stroke order. Out of 421 multiple-stroke flashes, 144 (34%) had at least one subsequent stroke whose field peak was greater than that of the first stroke. Significant differences were observed in lightning parameters for different storms, however, the majority of storms had similar lightning parameter statistics. No significant disparities were found between characteristics of Florida negative cloud-to-ground lightning obtained in this study and their counterparts from previous studies.

By using the moving average filtering, the percentage of flashes with detectable PB pulse trains increased from 22% to 46%. Thus, the detectability of PB pulse train is significantly affected by the signal-to-noise ratio of the recording system. Further, PB pulse train detectability can vary from one storm to another. The PB pulse trains of flashes with higher peak currents of the first return stroke and smaller distances to the observation point are more likely to be detected. Characteristics of PB pulse trains of negative CG lightning in Florida were examined. The average PB pulse train duration for 222 flashes is 2.2 ms. The AM and GM of PB-RS intervals are 24 ms and 19 ms, respectively. The AM and GM of PB/RS ratios are 0.23 and 0.15. Most flashes with short PB-RS intervals were associated with high peak currents.

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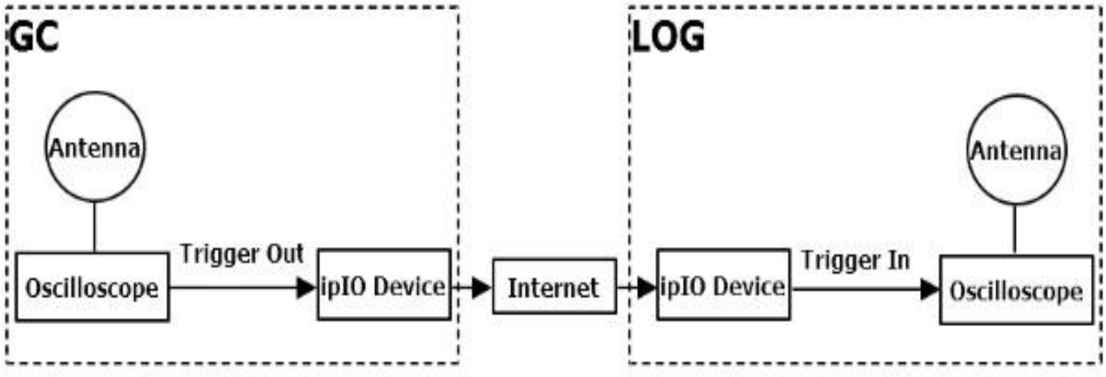

Fig. 1 Two-station (GC and LOG) measurement setup. When the electric field at GC exceeds the preset threshold, the oscilloscope is triggered and sends a trigger pulse via the ipIO devices and the Internet to the oscilloscope at LOG. Once triggered, the oscilloscope at LOG records the distant electric field of lightning that originally triggered the oscilloscope at GC.

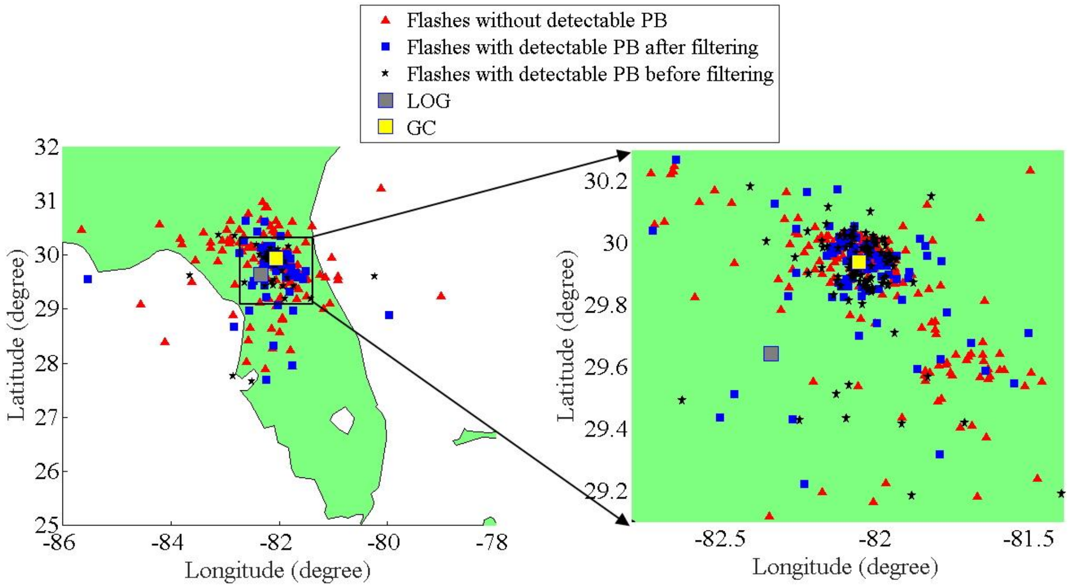

Fig. 2 Locations of 478 flashes (first strokes only) recorded at LOG and reported by the NLDN. The expansion of the black box area in the left panel is shown in the right panel.

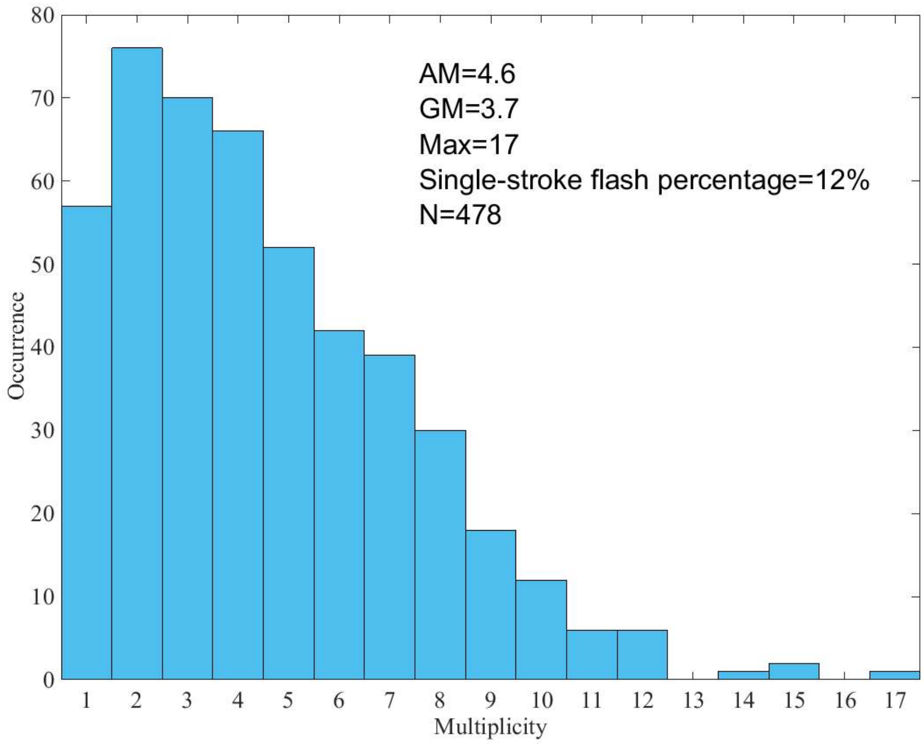

Fig. 3 Histogram of the number of strokes per flash (multiplicity).

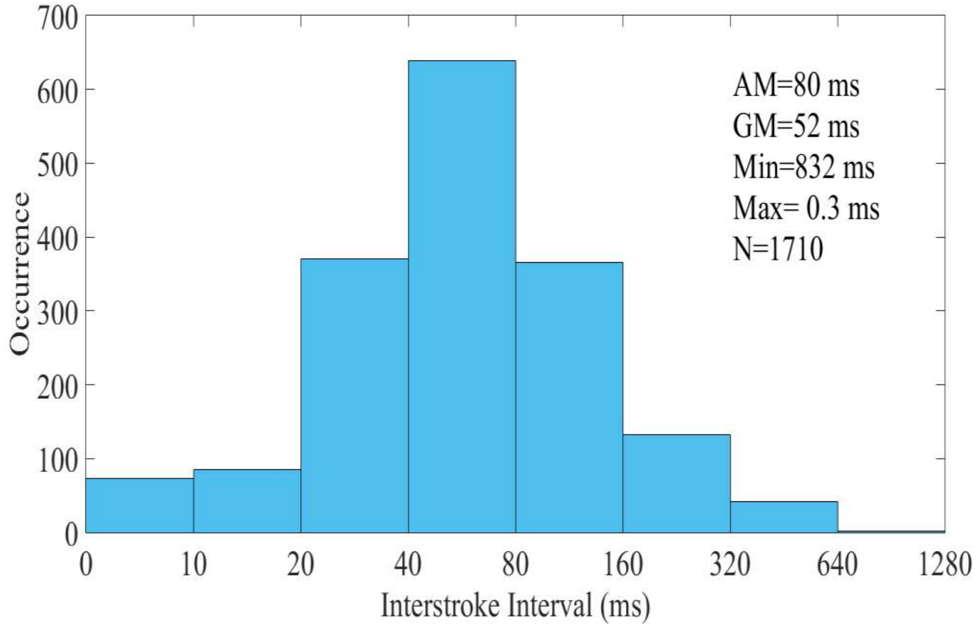

Fig. 4 Histogram of the interstroke interval.

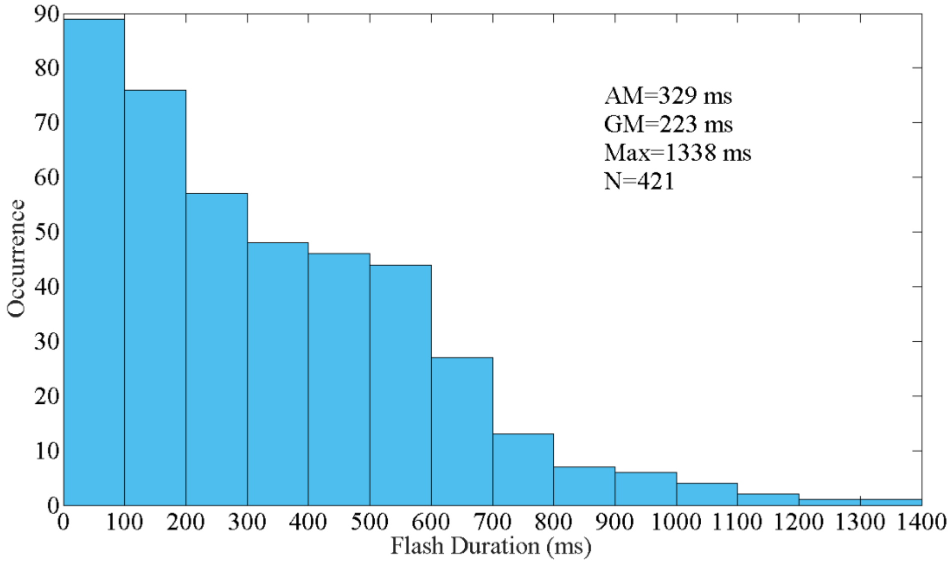

Fig. 5 Histogram of the flash duration.

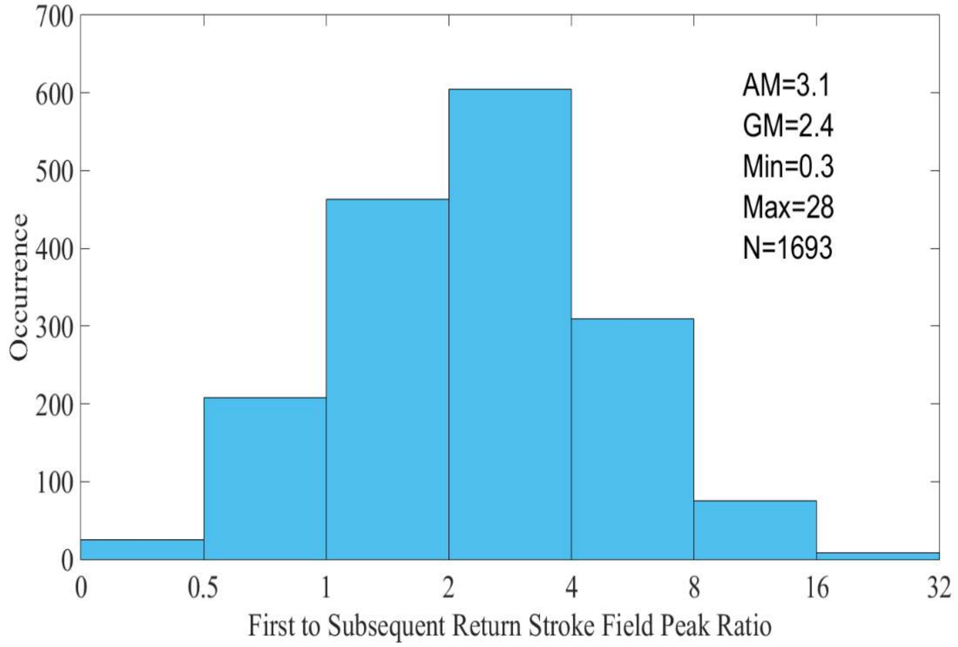

Fig. 6 Histogram of the ratios of the first to subsequent return stroke field peaks.

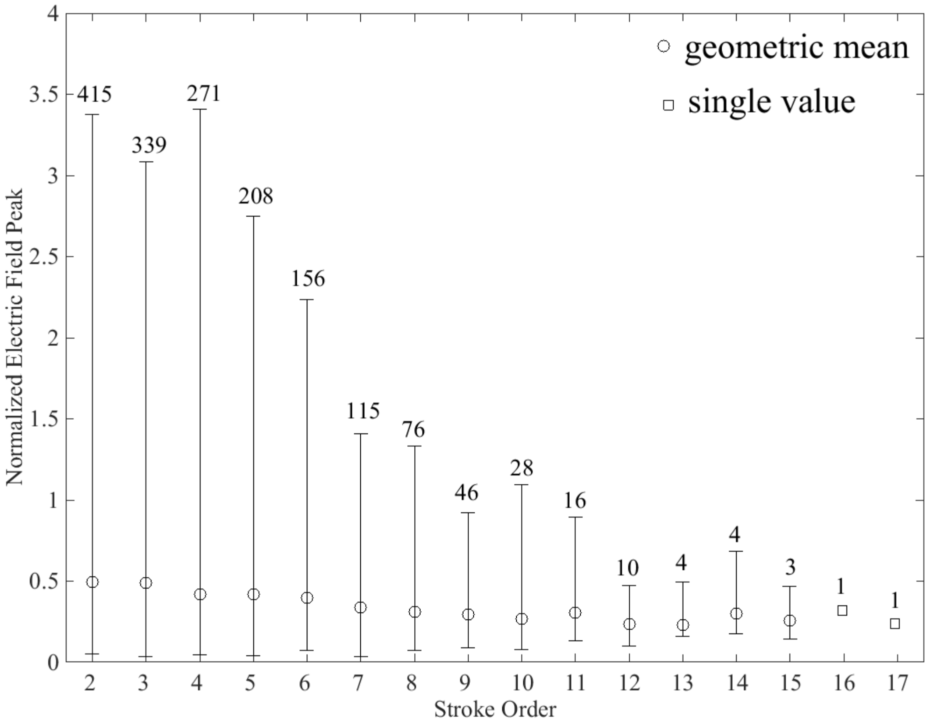

Fig. 7 Normalized electric field peaks for strokes of different order. Ranges of variation (vertical bars) and sample sizes (at the top of vertical bars) for subsequent strokes of different order are given.

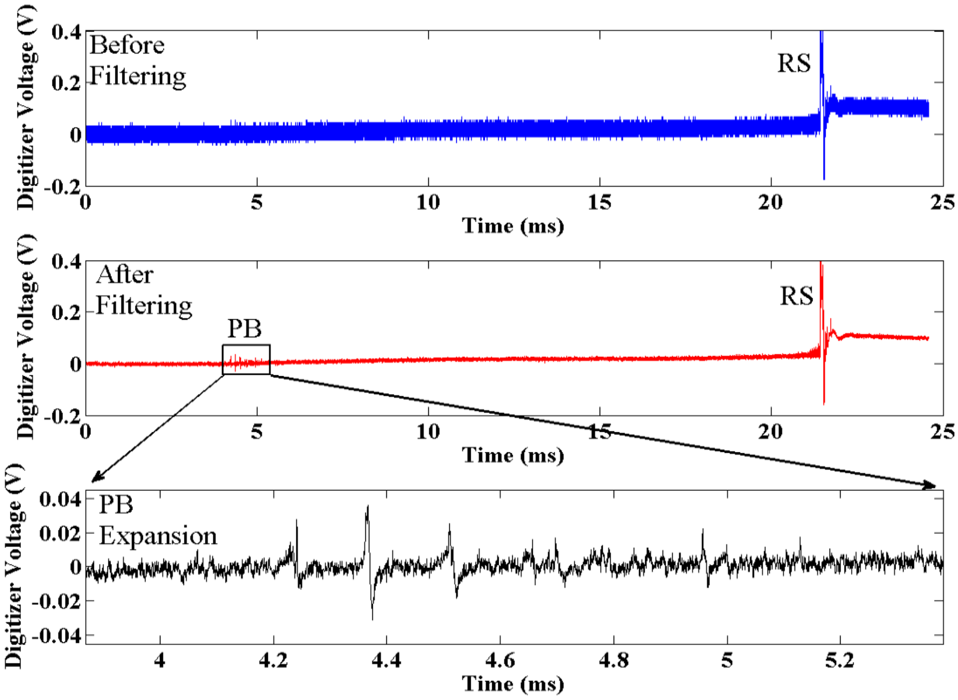

Fig. 8 Comparison of the electric field (in digitizer volts) waveforms before and after filtering. The top panel shows the waveform before filtering, in which no PB pulses can be seen. The same waveform after filtering, shown in the middle panel, exhibits a readily detectable PB pulse train around 5 ms. The bottom panel shows an expansion of the PB pulse train seen in the middle panel.

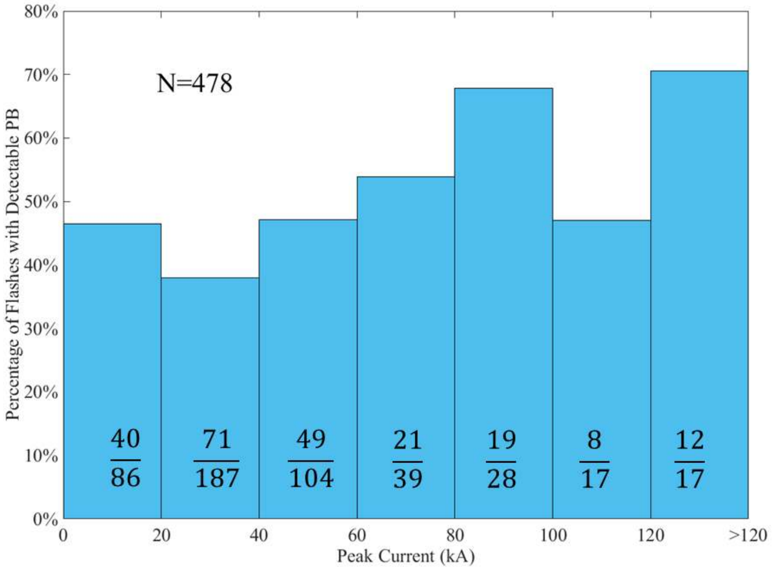

Fig. 9a The percentage of flashes with detectable PB pulse trains versus peak current of first return stroke reported by the NLDN for all 478 flashes. The denominator is the

sample size and the numerator is the number of flashes with detectable PB pulse trains.

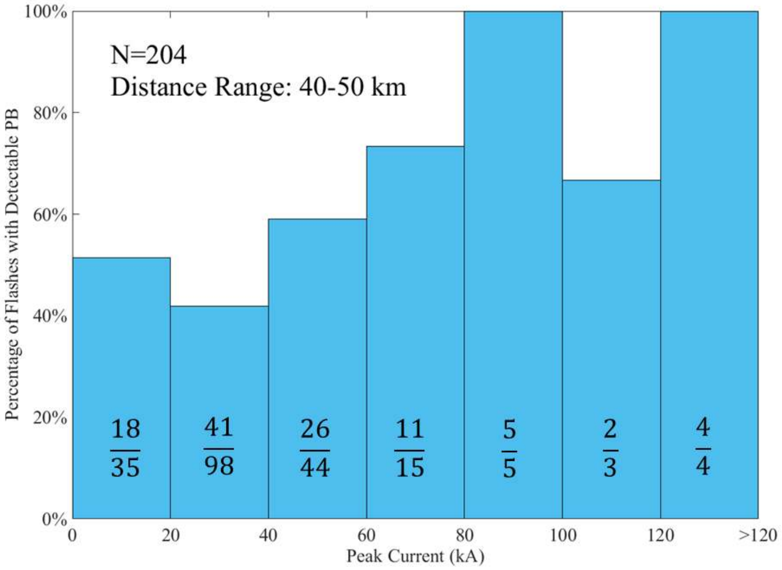

Fig. 9b The same as Fig. 9a, but for 204 flashes at distances ranging from 40 to 50 km.

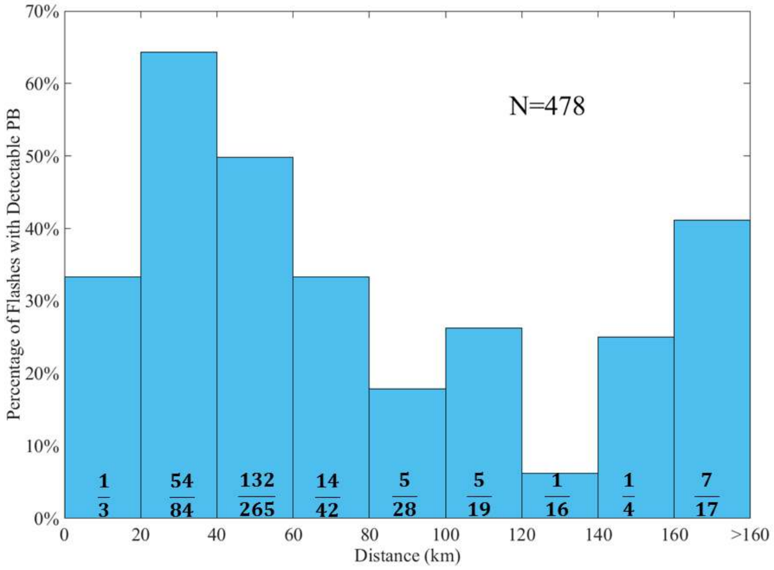

Fig. 10a The percentage of flashes with detectable PB pulse trains versus distance from the strike point to the observation point for all 478 flashes.

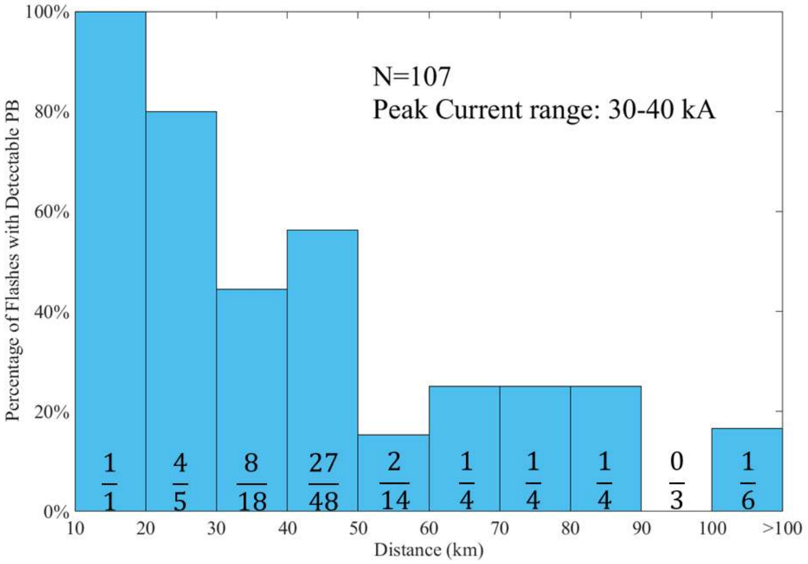

Fig. 10b The same as Fig. 10a, but for 107 flashes with first-stroke peak currents ranging from 30 to 40 kA.

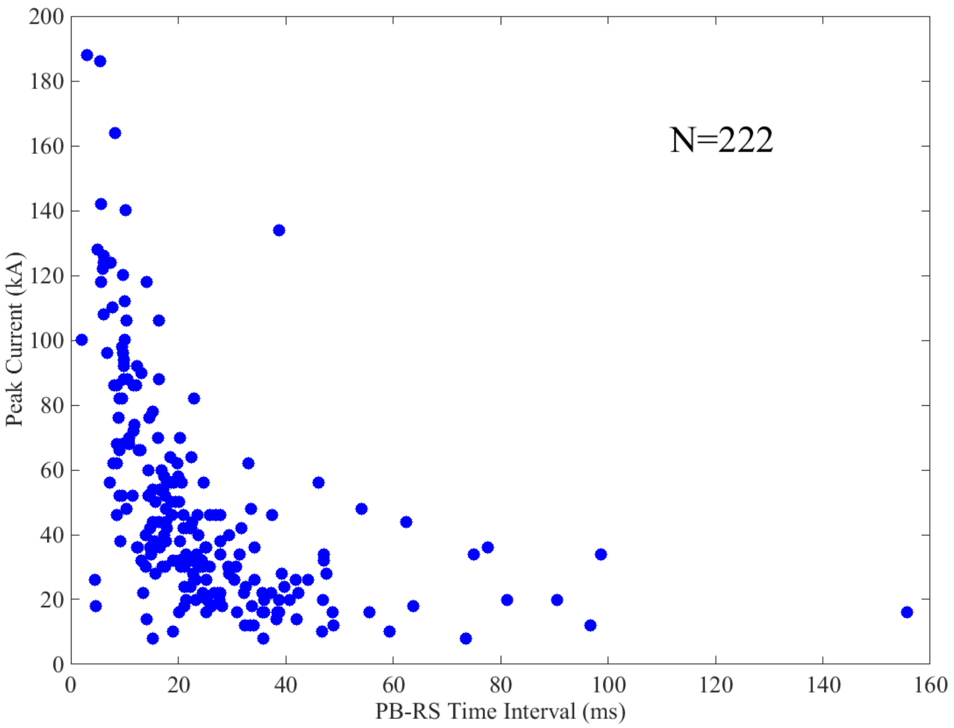

Fig. 11 Scatterplot of peak current versus time interval between the PB pulse train and RS

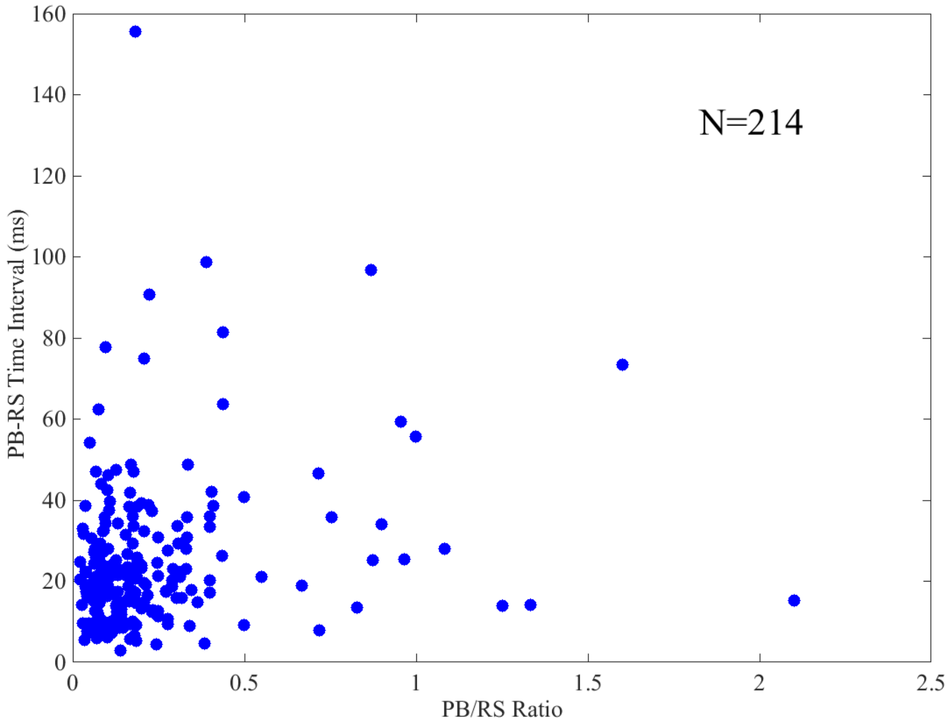

Fig. 12 Scatterplot of PB-RS time interval versus PB/RS ratio

Table 1 Summary of multiplicity of negative flashes and percentage of single-stroke flashes in different regions

Reference and Region	Average Number of Strokes per Flash (Multiplicity)	Percentage of Single-Stroke Flashes	Sample Size
Kitgawa et al. (1962), New Mexico	6.4	13%	83
Rakov et al. (1994), Florida	4.6	17%	76
Cooray and Jayaratne (1994), Sri Lanka	4.5	21%	81
Cooray and Perez (1994), Sweden	3.4	18%	137
Saraiva et al. (2010), Arizona	3.9	19%	209
Ballarotti et al. (2012), Brazil	4.6	17%	883
Baharudin et al. (2013), Malaysia	4.0	16%	100
Present Study, Florida	4.6	12%	478

Table 2 Summary of geometric mean interstroke intervals and flash durations (sample sizes are given in the parentheses)

Reference and Region	Geometric Mean Interstroke Interval, ms	Geometric Mean Flash Duration, ms
Rakov et al. (1994), Florida	60 (270)	-
Cooray and Jayaratne (1994), Sri Lanka	57 (284)	-
Cooray and Perez (1994), Sweden	48 (568)	-
Saraiva et al. (2010), Arizona	61 (598)	216 (169)
Saraiva et al. (2010), Brazil	62 (624)	229 (179)
Baharudin et al. (2013), Malaysia	67 (305)	-
Present Study, Florida	52 (1710)	223 (421)

Table 3 Summary of statistics on the ratio of the first to subsequent return stroke field peaks

Reference	Region	Arithmetic Mean	Geometric Mean	Sample Size
Nag et al. (2008a)	Florida	2.1	1.7	239
	Austria	2.3	1.6	247
	Brazil	2.4	1.9	909
	Sweden	2.4	1.9	258
Present Study	Florida	3.1	2.4	1693

Table 4
Variation of lightning parameters from one storm to another

Storm ID (mm/dd/yyyy)	Multiplicity				Interstroke Interval, ms					Flash Duration for Multiple-Stroke Flashes, ms					First to Subsequent Return Stroke Field Peak Ratio				
	Number of Flashes Recorded	AM	GM	Max	Sample Size	AM	GM	Min	Max	Sample Size	AM	GM	Min	Max	Sample Size	AM	GM	Min	Max
08/17/2013	25	4.6	4.0	10	90	95	72	11	488	24	356	242	44	756	88	2.7	2.0	0.4	12.5
08/22/2013	16	4.8	4.2	8	61	63	48	0.5	325	15	257	202	22	538	61	3.7	2.8	0.8	22.5
08/31/2013	88	5.1	4.3	17	365	82	61	0.9	760	83	363	276	31	1199	365	2.4	2.0	0.3	15.6
09/06/2013	17	3.5	2.8	8	43	82	63	7.5	345	12	294	219	51	601	41	3.1	1.9	0.4	25.1
05/15/2014	17	3.8	3.4	7	48	51	38	6	217	16	152	128	31	320	48	3.7	3.0	0.7	13.7
05/25/2014	19	4.5	4.0	8	66	74	52	13	450	18	273	208	38	644	66	3.5	2.8	0.3	11.3
05/28/2014	21	3.7	2.8	12	56	77	57	9	399	16	271	143	9	943	56	3.1	2.5	0.7	13.6
05/29/2014	21	3.7	2.7	11	56	76	48	0.8	42	15	284	138	17	1096	56	4.0	3.0	0.8	15.4
06/08/2014	31	4.7	3.8	11	114	76	56	0.4	294	28	309	228	44	649	114	2.2	1.7	0.3	9.1
07/03/2014	96	4.3	3.5	12	319	80	50	0.3	491	81	316	220	0.7	1016	319	3.0	2.3	0.3	14.9
07/05/2014	16	5.7	4.6	15	75	127	71	0.7	832	14	684	554	86	1338	73	2.8	2.3	0.4	8.7
07/07/2014	15	4.3	3.4	11	49	73	42	0.5	412	13	275	165	0.5	546	49	3.0	2.5	0.7	12.0
07/10/2014	15	4.2	3.6	10	48	58	35	0.7	289	14	200	130	21	613	48	4.2	2.9	0.5	15.2
07/25/2014	20	4.2	3.3	15	64	73	56	7.9	322	17	274	184	10	799	61	5.5	3.9	0.3	27
08/02/2014	24	6.1	5.0	14	122	94	51	0.6	615	23	511	386	73	1229	117	3.6	2.8	0.5	28.2
08/15/2014	20	4.7	3.8	11	74	58	41	0.6	236	18	237	139	0.6	777	71	4.7	3.8	0.6	16
08/23/2014	17	4.5	3.4	12	60	92	55	1.1	509	14	401	310	45	837	60	2.7	2.1	0.5	8.1
Total	**478**	**4.6**	**3.7**	**17**	**1710**	**80**	**52**	**0.3**	**832**	**421**	**329**	**223**	**0.5**	**1338**	**1693**	**3.1**	**2.4**	**0.3**	**28.2**

Table 5
Percentages of flashes with detectable PB pulses before and after filtering for 17 storms

Storm ID mm/dd/yyyy	**Number of Flashes Recorded**	**Percentage of Flashes with Detectable PB Pulses Train**	
		Before Filtering	**After Filtering**
08/17/2013	25	20%	60%
08/22/2013	16	38%	56%
08/31/2013	88	13%	30%
09/06/2013	17	18%	47%
05/15/2014	17	41%	59%
05/25/2014	19	21%	37%
05/28/2014	21	29%	62%
05/29/2014	21	52%	81%
06/08/2014	31	16%	42%
07/03/2014	96	6%	28%
07/05/2014	16	31%	69%
07/07/2014	15	33%	47%
07/10/2014	15	53%	100%
07/25/2014	20	15%	55%
08/02/2014	24	42%	58%
08/15/2014	20	45%	55%
08/23/2014	17	18%	35%
Total	478	22%	46%

Table 6
Characteristics of PB pulse trains in this study and those found in the literature

Parameters	**Reference**	**AM**	**GM**	**Min**	**Max**	**Sample Size**
PB Pulse Train Duration (ms)	Nag and Rakov (2009b)	3.4	3.2	1.1	5	12
	Present Study	2.2	1.7	0.2	16.4	222
PB-RS Interval (ms)	Baharudin et al. (2012)	22	18	3.3	92.5	100
	Marshall et al. (2014)	43	-	-	-	103
	Present Study	24	19	2	156	222
PB/RS Field Peak Ratio	Nag and Rakov (2009b)	0.62	0.45	5.1	0.16	59
	Baharudin et al. (2012)	0.29	0.22	0.03	1.5	100
	Marshall et al. (2014)	0.2	-	-	-	103
	Present Study	0.23	0.15	0.02	2.1	214