Some Characteristics of Multiple Stroke Negative Cloud to Ground Lightning Flashes in Padang

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Abstract: The characteristics of multiple stroke negative cloud to ground (CG) lightning flashes in Padang, Indonesia based on electric field recording were investigated. 100 negative CG lightning flashes containing 623 strokes, recorded from August to October 2014, were examined. It was observed that all first return strokes (RS) negative CG lightning flashes were preceded by preliminary breakdown pulses (PBPs). However, only 40% of the detecable PBP trains could be analyzed statistically on PBP train duration, PBP-RS separation, and PBP/RS ratio, while the detectable leader pulses was 69%. In addition, it was also found that the arithmetic mean (AM) and maximum number of strokes were 5.2 and 18, respectively. The AM and geometric mean (GM) interstroke interval were 55.34 and 34.71 ms, respectively. Furthermore, 2% of the subsequent return stroke (SRS) peak electric fields were larger than those of the first return stroke (RS). The AM and GM ratios of SRS/RS were 0.36 and 0.3, respectively.

Keywords: negative cloud to ground, preliminary breakdown, leader, return stroke, interstroke interval, peak electric field ratio

1. Introduction

Negative cloud to ground (CG) lightning flashes is the most common type of CG discharges and has thereafter studied by many authors. A CG lightning flash usually contains preliminary breakdown pulses (PBPs) in the cloud and downward stepped leader (SL) propagation followed by a first return stroke (RS). The characteristics of a negative CG could largely be determined by the magnitude of the so called lower positive charge regions (LPCR) [1-4]. A larger LPCR causes the direction of negative leader propagation to be predominantly horizontal, even though finally the stepped leader propagates toward the ground. Meanwhile, a smaller LPCR causes negative stepped leader propagation to be predominantly vertical [5-6]. The time separation between PBPs and RS is approximately several milliseconds to hundreds of milliseconds. The generated electric field signature differentiates these processes. Nag and Rakov [5] stated that in negative CG lightning flashes, PBPs may not be detected on the first return stroke when the magnitude of the LPCR is very small. They claimed that CG lightning flashes vary in detectable PBP percentage according to latitude. Higher latitudes have a higher percentage of detectable PBPs than lower latitudes. In contrast, many researchers have argued that the first return stroke always involves PBPs in all negative CG flashes [7-9]. Their studies revealed that the detectable PBP percentage does not depend on latitude. A PBP can be detected if the amplitude of the PBP is above the noise level of the environment and electric field change sensors. However, Marshall et al. [9] have stated that they "cannot be certain that detection of PBPs always equals 100%" for all latitudes. In a more recent study, Zhu et al. [10] found that PBP detectability is not only affected by the sensor noise level but also by storm type, RS peak current and observation distance. The differences in previous mentioned results are our motivation to investigate the characteristics of negative CG in Padang at low latitude.

Further, the characteristics such as the number of strokes in one flash, the interstroke interval and the subsequent to first return stroke (SRS/FRS) ratio will be discussed in this paper. This paper reports the results of investigations based on measurements of the electric

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field for the characterization of negative cloud to ground lightning flashes in tropical climate and comparison with results from other investigations at various locations. As far as we know, this is the first comprehensive study conducted on this subject in Padang, Indonesia.

2. Observation and Data

This research was conducted from August to October 2015 in Padang, Indonesia (0° N) on 56 thunderstorm days. An electric field antenna/sensor was located at an altitude of 317 m above sea level and 13 km from Padang Beach, Indian Ocean, as shown in Google Maps© in Figure 1. A parallel flat-plate fast antenna configuration was used to detect the electric field changes in the thunderclouds. The fast antenna was connected to a buffer and integrator with a time constant of 100 ms. Furthermore, all signals detected by this antenna were recorded by a digitizer with a sample rate of 1 MS/s, a sample interval of 1 µs, and a recording length of 1 s. To ensure that cloud to ground lightning was recorded, the digitizer was set to window trigger mode at a trigger level of 1 V and a pretrigger time of 300 ms. More details about the measurement system for electric field recording are described in Hazmi et al. [11].

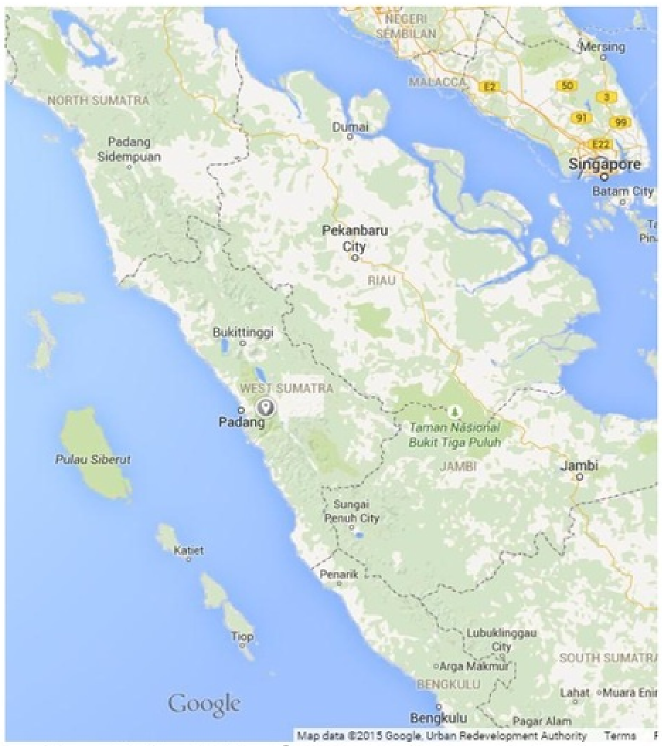

Figure 1. Google Maps© of electric field sensor location.

In this study, we utilized the physics sign convention to examine the electric field changes. By using the features of the electric field waveform of return strokes [12-14], the distance of the flashes was estimated at about 15-150 km. The peak current amplitudes I at strike distances larger than 50 km were calculated by the ionospheric reflection height h_I [13] and an empirical formula I [15]. We assumed that the h_I values for daytime and nighttime were 81 km [14] and 85 km [12], respectively.

$$h_1 = R_e\left[\cos^2\left(\frac{D}{2R_e}\right)-1\right]+\sqrt{\left\{R_e^{\,2}\left[\cos^2\left(\frac{D}{2R_e}\right)-1\right]+\left(\frac{ct_1+D}{2}\right)^2\right\}} \qquad (1)$$

where R_e is the mean radius of the earth, D is the distance to the strike points, t_1 is the difference in arrival time of the first sky wave and the ground wave, and c is the velocity of light.

$$I = 1.5 - 0.037 * D * E \qquad (2)$$

where I is the return-stroke peak current (kA), E is the electric field peak (V/m), and D is the distance to the strike point (km).

3. Results and Discussion

In this study, we examined characteristics of negative cloud to ground lightning flashes such as detectability of PBP, PBP duration, PBP-RS separation, PBP/RS ratio, SL duration, number of strokes per flash, interstroke interval, and electric field peak ratio of SRS/FRS. The data of 100 selected negative cloud to ground lightning flashes were collected in a data set. 78% of the CG flashes occurred at a distance larger than 50 km from the sensor based on the RS electric field waveform characteristics. A summary of the PBP, SL and RS characteristics is listed in Table 1. PBP train duration, stepped leader duration, PB-RS separation, and PB/RS ratio are compared to previous results from other researchers and regions for negative CG lightning flashes in Table 1. In addition, the characteristics of the electric field waveforms from multiple strokes were also compared with different locations and latitudes, as shown in Table 2.

A. Characteristics of Preliminary Breakdown Pulse

A.1 Detectability of PBP

Table 1. Summary of Preliminary Breakdown.

Parameters	Researcher	Sample	AM	GM	SD	Min	Median	Max
PB Pulse Train (ms)	This study	40	1.39	1.30	0.53	0.47	1.26	3.40
	Zhu et al. [10]	222	2.20	1.70	-	0.20	-	16.40
	Wu et al. [6]		0.67	-	-	0.13	-	2.80
	Baharuddin et al. [7]	24	12.30	10.10	-	2	-	37
	Nag and Rakov [5]	12	3.40	3.20	-	1.10	-	5
PB-RS Separation (ms)	This study	40	8.23	7.54	3.92	3.79	6.87	19.08
	Zhu et al. [10]	222	24	19	-	2	-	156
	Marshal et al. [9]	103	43	-	-	-	-	-
	Wu et al. [6]	-	3.60	-	-	-	-	-
	Baharuddin et al. [7]	100	22	18	-	3.30	-	92.50
PB-RS Peak Ratio	This study	40	0.13	0.11	0.08	0.03	0.10	0.37
	Zhu et al. [10]	214	0.23	0.15	-	0.02	-	2.10
	Marshal et al. [9]	103	0.20	-	-	-	-	-
	Wu et al. [6]	-	0.47	-	-	-	-	-
	Baharuddin et al. [7]	97	0.27	0.14	-	0.03	-	2.20
Leader Duration (μs)	This study	69	272	213	306	79	195	2500

The electric field waveforms of PBPs were recorded and it was found that there were two types of PBPs. For convenience we will call them type A and type B. Type A is defined as a regular PBP train, described by Nag and Rakov in [4]. Type B is defined as an irregular PBP train, containing several pulses that usually have a small magnitude and the time interval between the first and the second pulse can be more than 2 ms. Types A and B are as shown in Figure 2. Only 40 out of 100 first return stroke (40%) were a detectable PBP of type A. This indicates that there are several factors that affect PBP detectability, such as sensor noise level, RS peak current and observation distance [9,10]. Furthermore, we estimated 78 out of 100 first return stroke peak currents by using Equations (1) and (2). According to Equation (2), the electric field peak is proportional to the peak current. The obtained results show that the AM and GM peak currents were 48 and 45 kA, respectively, in the range of 15-111 kA for distances of about 50-150 km. Figure 3 explains the previously mentioned factors. The numbers for type A and type B were 40 and 38, respectively. The relationship between RS peak current versus observation distance can be seen in Figure 3. The relationship between peak current and distance for detectability of types A and B was not strong enough. For the observation distance range of 50-150 km, we speculate that detection of the PBP train is not only affected by the sensor noise level but also by the LPCR and charge movement of each storm type. More data are necessary to clarify the possibility of type A needing a longer pretrigger time (600 ms) of the measuring system for all negative CG lightning flashes. However, we agree with Marshall et al. [9] that all negative CG lightning flashes clearly involve PBPs to initiate leader propagation to the ground.

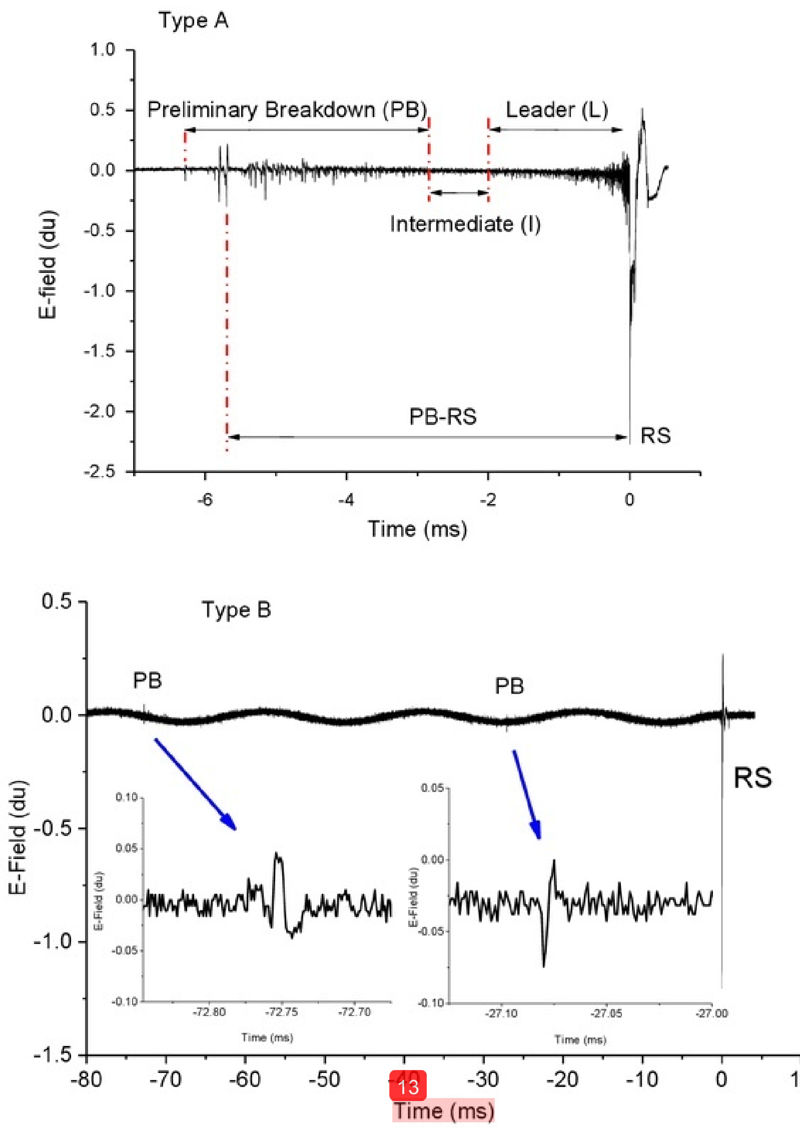

Figure 2. Typical electric field waveform of preliminary brekadown pulses for type A and B.

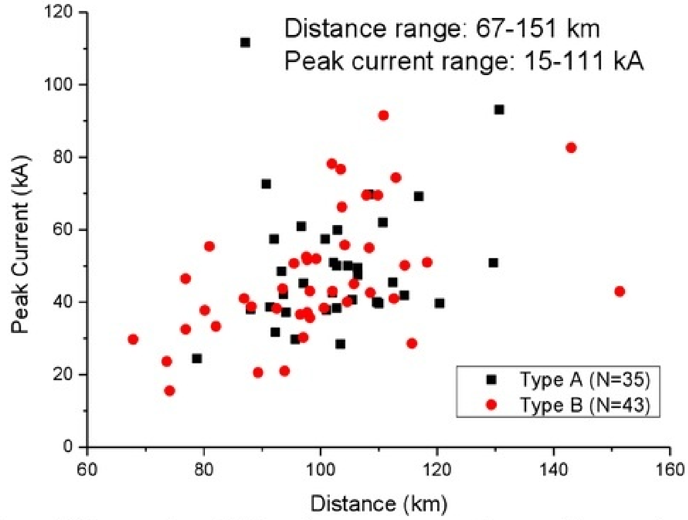

Figure 3. Scatter plot of RS peak current versus distance for type A and B.

A.2. PBP train duration

The histogram of PBP train duration can be seen in Figure 4. Figure 4 shows that the PBP train duration varied for each thunderstorm day. The arithmetic mean (AM), the geometric mean (GM) and the standard deviation (SD) of the PBP train duration for type A were found to be about 1.39 ms, 1.3 ms and 0.53 ms, respectively. The minimum, the median and the maximum values of type A observed were 0.47 ms, 1.26 ms and 3.4 ms, respectively.

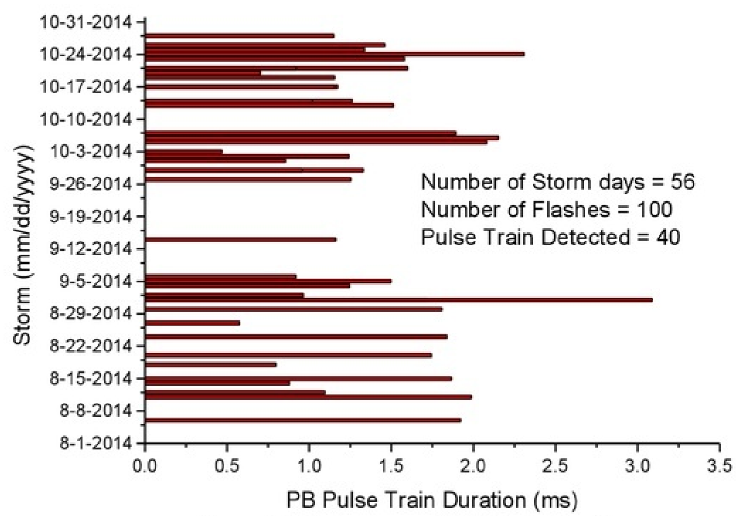

Figure 4. Histrogram of PBP train duration

For comparison, the AM values for different regions and seasons reported previously by Zhu et al. [10], Baharuddin et al. [7], and Nag and Rakov [4] were 2.2 ms, 12.3 ms, and 3.4 ms respectively in summer. Wu et al. [6] reported 0.67 ms in winter. Our AM value is the smallest PBP train duration from the summer season and larger than that in winter. We predict that the difference in PBP train duration has a relation to storm type.

A.3. PB-RS Separation

PB-RS separation is defined as the time interval between the highest peak of the PBP train to the highest peak of the following RS. From this study it was found that the AM, the GM, and the SD of the PB-RS separation were 8.23 ms, 7.54 ms and 3.92 ms, respectively. The minimum, the median and the maximum values of the separation were 3.79 ms, 6.87 ms and 9.08 ms, respectively. Meanwhile, the AM value from previous studies as reported by Zhu et al. [10], Marshall et al. [9], Wu et al. [6] and Baharuddin et al. [7] were 24 ms, 43 ms, 3.6 ms and 22 ms, respectively. We cannot explain why our average value was smaller than that from other locations in summer. It may be due to data limitations, different storm types or the season. However, the present study showed that the minimum value of the PB-RS separation for Sumatra and Malaysia, whose latitudes are similar, was almost the same.

A.4. PB/RS ratio

The PB/RS ratio is considered as the electric field ratio between the highest peak of the PBP train and the following first return stroke. It was found that it ranged from 0.03 to 0.37 with AM, GM, SD, while the median values were 0.13, 0.11, 0.08 and 0.1, respectively. Furthermore, the AM values from previous researches at different latitudes, as reported by Zhu et al., (29°) [10]; Marshall et al., (29°) [9]; Wu et al., (35°) [6] and Baharuddin et al., (1°) [7], were 0.23, 0.20, 0.47, and 0.27, respectively. Our AM and GM values were 2-4 time smaller than those from the different regions and seasons reported by other researchers. Clearly, the PB/RS ratio has no relation with latitude.

A.5. Leader Duration

In this section, we define the leader duration as the time interval from the initial leader pulses (stepped leader) detected in the leader stage, as stated by Clarence and Malan [1] and Marshall et al. [9], until the succeeding RS, as shown in Figure 5. Because the initiation of stepped leaders is difficult to identify, only leader pulses with twice the amplitude of the noise level were considered in this study. It was found that for only 69 out of 100 first return stroke, a leader step could be detected. For the remaining 31 flashes no leader pulses were detected due to their small amplitude. The leader duration ranged from 79 μs to 2500 μs with AM, GM, SD and median value at 272 μs, 213 μs, 306 μs and 195 μs, respectively. Clarence and Malan [1] have reported that the leader stage ranged from 4-30 ms. Our leader duration range was far smaller than that of Clarence and Malan's observations [1]. The differences may be caused by sensor noise level, observation distance or storm type.

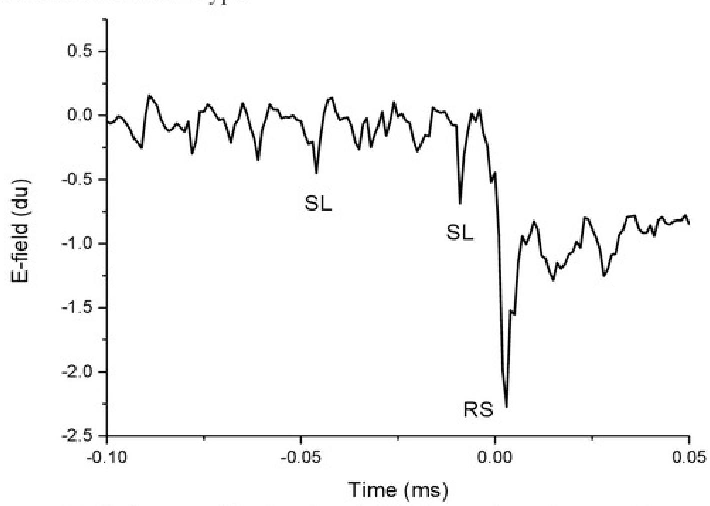

Figure 5. Typical stepped leader electric field waveform for negative ground flash

B. Characteristics of Return Stroke

B.1.. Number of strokes

Typical return stroke electric field waveforms of multiple strokes recorded in Indonesia are shown in Figure 6. An expanded first return stroke electric field waveform from Fig. 6 shown in Figure 7. In this section, a summary of the number of flashes, mean and maximum number of strokes per flash based on the accurate-stroke-count method is presented in Table 2. Table 2 also provides a comparison with other researches for different locations with variation in latitude and type of storms. This study revealed that the mean and maximum number of strokes value of lightning flashes in Indonesia is 5.2 and 18 respectively. The distribution of the number of subsequent strokes per flash in Indonesia is displayed in Figure 8. From Table 2, other tropical locations such as Malaysia (1°N) [16], Sri Lanka (5.9°N) [3], the mean and maximum value are 4, 4.5, and 14, 12, respectively. Comparing tropical locations, the highest number of multiple strokes occurs in Indonesia. For subtropical locations such as Brazil (22.6°S and 23.2°S) [17], Florida (29°N) [10], the mean and maximum value is 3.8, 4.6 and 16, 17, respectively. Takagi et al. [18] reported that the maximum number of multiple strokes that occurred in Japan (35°N) in a winter thunderstorm was 17. From Table 2 it can also be seen that tropical locations (Indonesia, Malaysia, Sri Lanka) have an average multiple stroke number that is almost the same as for subtropical locations (Brazil, Florida, Japan,), Furthermore, comparing the maximum number of strokes between tropical and subtropical locations, the obtained results show no significant difference between locations with various latitudes. The difference may be caused by seasonal influences and thunderstorm types.

Table 2. Summary of multiple strokes per flash

Researcher	Location	Number of flashes	Mean multiple stroke	Maximum multiple stroke
This study	Indonesia, 0° N	100	5.2	18
Baharudin et al. [16]	Malaysia, 1°N	100	4	14
Cooray and Jayaratne [3]	Sri Lanka, 5.9° N	81	4.5	12
Saba et al. [17]	Brazil, 23.2° S and 22.6°S	233	3.8	16
Zhu et al. [10]	Florida, 29°N	478	4.6	17
Takagi et al. [18]	Japan, 35° N	20	-	17

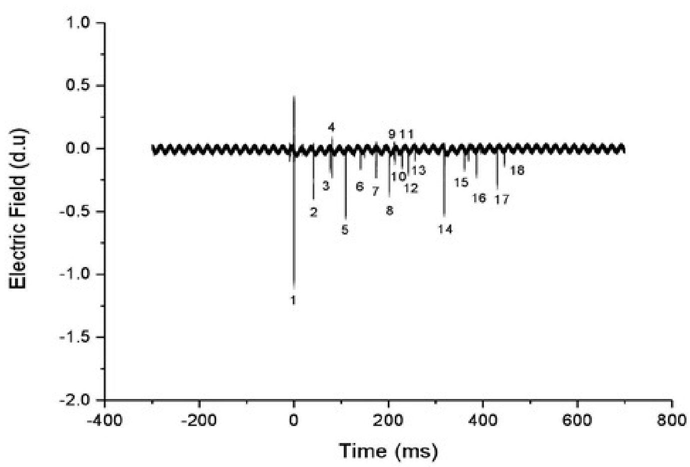

Figure 6. Typical negative electric field waveform record of eighteen strokes ground flash within 1 second in Padang.

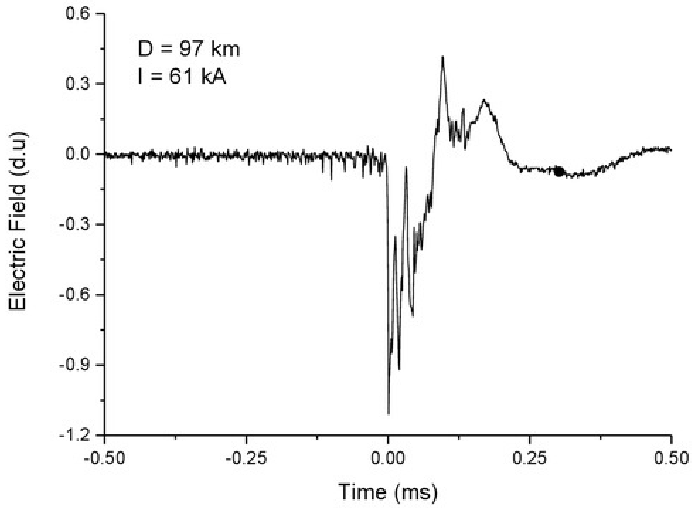

Figure 7. An expanded negative first return stroke electric field waveform from Figure 6 on 1 ms.

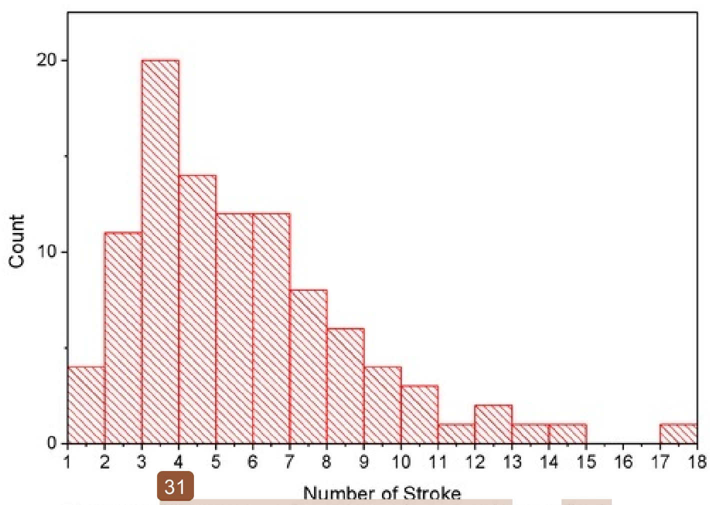

Figure 8. Histogram of number of strokes in one flash

B.2. Interstroke interval

One of the important parameters of negative cloud to ground lightning flashes characteristics is the interstroke interval. Figure 9 displays interstroke interval of multiple strokes in negative cloud to ground lightning flashes. In this study, we analysed 523 subsequent return strokes (SRS) of 100 lightning flashes. The obtained results show that the minimum, maximum, arithmetic mean (AM), and geometric mean (GM) interstroke intervals were 0.10, 582.4, 55.34 and 34.71 ms, respectively. For comparison, the GM found by other researchers in Malaysia (1°N) [16], Sri Lanka (5.9°N) [3], Brazil (22.6°S and 23.2°S) [17], Florida (29°N) [10], were 67, 56.5, 61, 61, and 52 ms, respectively. Takagi et al. [18] reported that the AM value in winter and summer thunderstorms in Japan (35°N) was 17 and 90 ms, respectively. Our AM and GM values are smaller than those from other locations, except the results obtained in Japan in winter thunderstorms. The observed results indicate that the interstroke interval does not depend on location with latitude variation. The interstroke intervals of lightning flashes at the same location have different characteristics between summer and winter, as reported by Takagi et al. [18]. Furthermore, Figure 10 shows the distribution of separation time (interstroke interval) between the first return stroke and subsequent return strokes. The histogram of return stroke order indicates that there is no systematic time variation patterns of interstroke interval from one stroke to the subsequent stroke, as shown in Table 3. The same results also reported by Miranda et al., [19] and Baharuddin et al., [16]. The interstroke interval is also related to the distance between strike points. According to Takagi et al., [18], the AM distance between strike points is 1.3 km in winter and 1.9 km in summer, respectively.

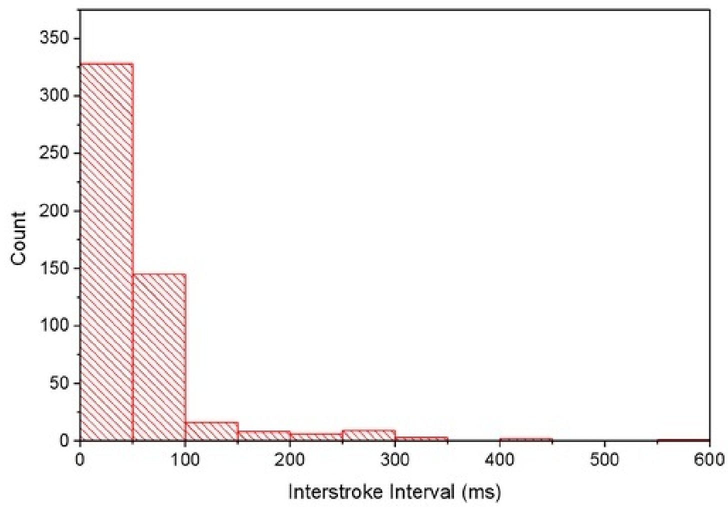

Figure 9. Histogram of interstroke interval of multiple stroke in negative lightning flashes

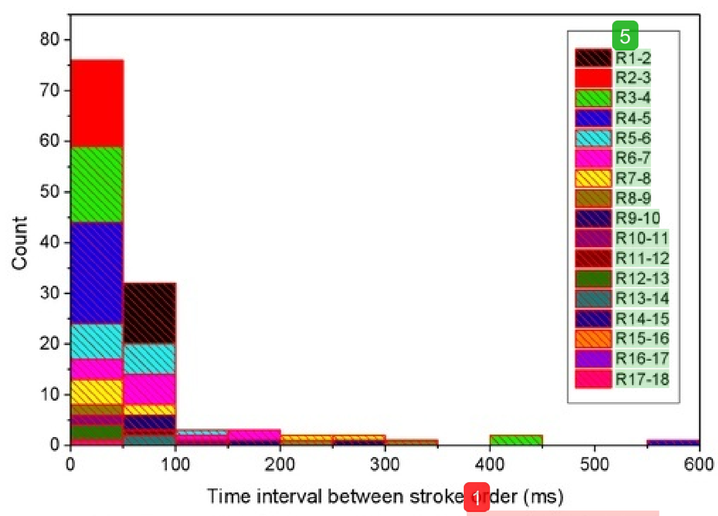

Figure 10. Histogram of return stroke order interstroke interval

Table 3. Summary of interstroke interval of negative return strokes

Researcher	Data	Number of Subsequent Return Stroke	Min (ms)	Max (ms)	AM (ms)	GM (ms)
This study	100	523	0.1	582.4	55.34	34.71
Baharudin et al. [16]	100	305	0.5	461	86	67
Cooray and Jayaratne [3]	81	284	0.98	509	82.8	56.5
Saba et al. [17]	233	608	2	782	83	61
Zhu et al. [10]	478	1710	0.3	832	80	52
Takagi et al. [18]						
Summer	316	101	-	-	90	-
Winter	54	45	-	-	17	-

B.3. Return stroke electric field peak ratio

The first return stroke electric field peak and peak current in multiple strokes are usually the highest initial peak amplitude. The first return stroke electric field peak is the most important parameter for the design of lightning protection in power systems [1]. Generally, the maximum first return stroke electric field peak is about 200-300% higher than that of the subsequent return stroke [16-18]. In this study, 523 data of subsequent return stroke electric fields were analyzed. The electric field peak ratios of subsequent return stroke to first return stroke are summarized in Table 4.

Table 4. Ratio of electric field peak SRS/RS

Researcher and Location	Number of Subsequent Return Strokes	Min	Max	AM	GM	SD
This study, Indonesia	523	0.05	2.97	0.36	0.3	0.27
Baharudin et al. [16], Malaysia	301	0.13	2.8	0.73	0.6	0.48
Cooray and Jayaratne [3], Sri Lanka	284	0.03	2.3	0.55	0.44	-
Nag et al. [20]						
Florida	239	0.13	8.3	0.75	0.58	-
Sweden	258	0.08	3.3	0.64	0.52	-
Brazil	909	0.08	4.3	0.69	0.53	-
Austria	247	0.04	3.7	0.87	0.64	-

The obtained results show that the minimum, maximum, AM and GM electric field peak ratios of subsequent return stroke to first return stroke were 0.05, 2.97, 0.36 and 0.3, respectively. Next, the standard deviation of the electric field peak ratio was 0.27. This study showed that about 2% of the maximum values from the subsequent return strokes were larger than those of the first return strokes. The distribution of the electric field peak ratios of SRS/FRS is shown in Figure 11. In the previous studies, other researchers in Malaysia, Sri Lanka, Brazil, Florida, Austria, and Sweden found that the percentages of subsequent return stroke electric field peak larger than that of the first return stroke were 19, 15, 20, 21, 22.6, 32 and 18%, respectively. This may be caused by the difference in type of thunderstorms. The AM and GM ratios investigated by other researchers in Malaysia (1°N) [16], Sri Lanka (5.9°N) [3], Brazil (22.6°S and 23.2°S) [17], Florida (29°N) [20], Austria (47°N) [20], and Sweden (59.8°N) [20] were 0.73, 0.55, 0.69, 0.7, 0.75, 0.87, 0.64 and 0.6, 0.44, 0.53, 0.42, 0.46, 0.58, 0.64, 0.52, respectively. Compared with other locations, such as Malaysia, Sri Lanka (tropical regions) and Brazil, Florida, Austria, Sweden (subtropical regions), our AM and GM values were slightly lower. However, these observation results indicate that there are no significant differences in the electric field peak ratio between tropical and subtropical locations. The differences may be due to the instrumentation system, seasonal influences or storm types.

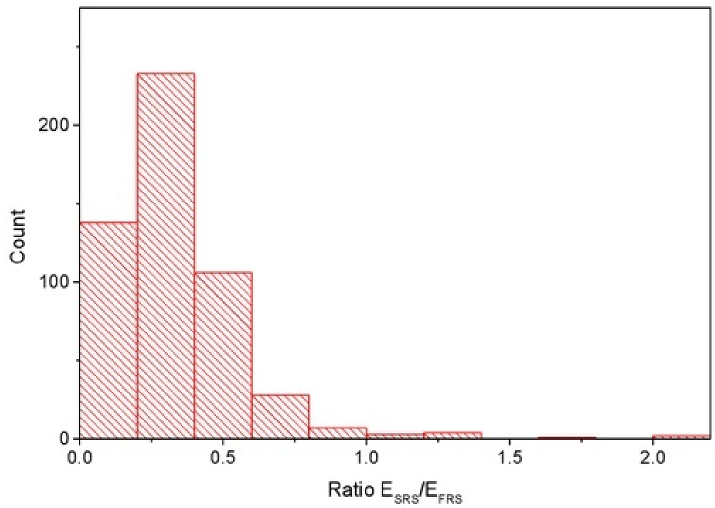

Figure 11. Histogram of electric field peak SRS/RS ratio

4. Conclusion

A data set containing 100 negative cloud to ground lightning flashes and 523 subsequent return strokes based on electric field recording was examined statistically. All first return stroke negative CG lightning flashes clearly involved PBPs to initiate leader propagation to the ground. PBP detectability was affected by sensor noise level, LPCR and variation of storm type. From our observations, the mean and maximum number of strokes recorded within 1 second with a time interval of 1 µs were 5.2 and 18 strokes respectively. Furthermore, the AM and GM interstroke intervals were 55.34 and 34.71 ms respectively. The AM and GM ratios of subsequent return stroke to first return stroke (SRS/RS) were 0.36 and 0.3 respectively. From a comparison with other researches, it was found that some characteristics of negative cloud to ground lightning flashes, i.e. the number of strokes, the interstroke interval, and the SRS/RS ratio, do not depend on geographical region or latitude. Differences in characteristics may be caused by seasonal influences, type of thunderstorm or measurement method. More data are needed to further investigate the multiple stroke characteristics of negative cloud to ground lightning flashes. Faults on power transmission and distribution lines can be caused by multiple strokes and high electric field peaks of lightning flashes.

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