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Comparative study on preliminary breakdown pulse trains observed in Johor, Malaysia and Florida, USA

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ABSTRACT

In this paper, the preliminary breakdown (PB) pulse train preceding the negative first return stroke (RS) is recorded using a broad band antenna system. These analyses were carried out in Johor Bahru, Malaysia and Florida, United States. This is a novel initiative at examining and identifying the characteristics of the PB pulse trains in the negative cloud-to-ground flashes observed in Malaysia. The arithmetic mean of the total pulse train duration is 12.3 ms and the weighted arithmetic mean of the pulse durations and interpulse intervals are 11 μ s and 152 μ s, respectively. The arithmetic mean ratio between the maximum peak amplitude of the PB pulse and the peak RS electric field was 27.8%, and the corresponding value in Florida was 29.4%. The arithmetic mean of the time duration between the most active part of the pulse train, and the RS was 57.6 ms in Malaysia and 22 ms in Florida. A qualitative comparison of our results with those obtained earlier in Sri Lanka, Sweden and Finland supports the hypothesis that the PBP/RS ratio is higher in the northern regions compared to the tropical regions.

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1. Introduction

The first electric field signature generated by a ground lightning flash sometimes produces a pulse train of relatively large microsecond-scale electric field pulses known as the preliminary breakdown (PB) pulse train. The characteristic features of PB pulse trains in negative cloud-to-ground flashes have been reported by Clarence and Malan (1957), Kitagawa and Brook (1960), Beasley et al. (1982), Brook (1992), Cooray and Scuka (1996), Gomes et al. (1998), Cooray and Jayaratne (2000), Gomes and Cooray (2004), Mäkelä et al. (2008), and Nag and Rakov (2009). These pulse trains may provide information concerning the first event that led to the electrical breakdown in the cloud. Any differences in the PB pulse trains in different geographical regions may indicate differences in the initial breakdown

processes in the clouds. For this reason, it is important to analyze and compare the features of these pulse trains in different geographical regions.

Gomes et al. (1998) and Cooray and Jayaratne (2000) analyzed and compared the ratios of the amplitude of electric field peaks of the initial half-cycle of the largest PBP train and the corresponding first return strokes (RS) in Sweden and in Sri Lanka. They observed that the ratio is much higher in Sweden than in Sri Lanka. They suggested that the reason for this difference is the weaker positive charge pocket in tropical thunderclouds compared to those observed in higher latitudes. Mäkelä et al. (2008) duplicated the study with a larger data sample and came to the same conclusion. However, the data available in the literature on PB pulses from tropical thunderclouds is scarce, and there is a need to gather more data from tropical thunderclouds. In the present study we have recorded the electric fields, including the PB pulse trains generated by lightning flashes in Johor and Florida. To the best of our knowledge this is the first time in Malaysia that the electromagnetic fields generated by the whole flash

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occurring with several nanosecond temporal resolutions have been recorded. The thunderstorms that generated the lightning flashes recorded in this study occurred approximately at distances of 10–100 km from the measuring station.

2. Data

In Malaysia, the measurements were recorded from April to June 2009 during the southwest monsoon period in the Johor state. Johor is located at the southern part of Peninsular Malaysia, in close proximity to the equator (1°N , 103°E). The measuring station was located on land at a location which is 132 m above sea level and approximately 30 km away from

the Tebrau Straits. Measurements were also recorded during the summer of 2009, i.e. July and August, in Florida. The measuring station was located at Florida Institute of Technology, in the vicinity of the eastern coast of Florida (27°N , 80°W). The measurement set up in Florida was identical to that used in Malaysia.

We used fast electric field measuring antenna system which is identical to the one described by Cooray and Lundquist (1982). The vertical electrical field was sensed by a flat plate antenna. The plane of the antenna is oriented perpendicular to the electric field vector or parallel to the ground in order to avoid the horizontal component of electric field. The effective height of the antenna is 0.25 m and the physical height is 1.5 m. A 60 cm long coaxial cable (RG58) was used

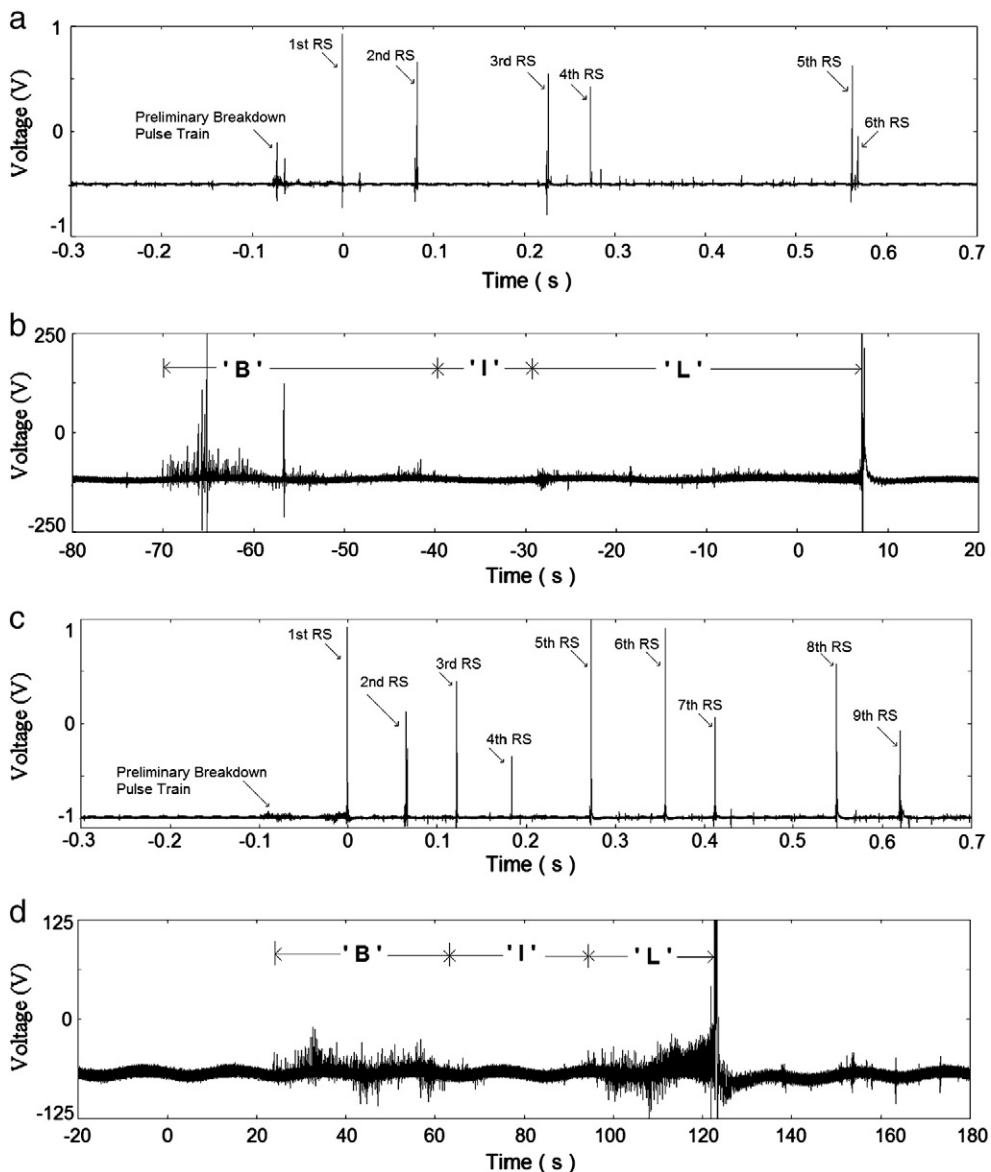


Fig. 1. Two examples of negative cloud-to-ground lightning flashes showing a pronounced preliminary breakdown pulse train, intermediate, and step leader that can be fitted to 'B, I, L' (description of Clarence and Malan, 1957) form. (a) Recorded in 29/05/2009 at 7:18:36.984578 (utc) with 1 s of time frame. (b) Close up from (a) with time frame of 100 ms. (c) Recorded in 29/05/2009 at 06:53:59.726016 (utc) with the time frame of 1 s. (d) Close up from (c) with time frame of 200 ms.

to connect the antenna to the electronic buffer circuit. After passing through the electronic buffer circuit, the signal from the antenna is fed by 10 m long coaxial cables (RG-58) into 12-bit digital transient recorder (Yokogawa SL1000 equipped with DAQ modules 720210) with 50 ns resolution. The sampling rate was set to 20 MS/s with the total length of recorded waveforms being 1 s. The trigger setting of the oscilloscope was such that signals of both polarities could be captured. The trigger level is set either 50 mV to 500 mV for the far flashes or 500 mV to 2 V for the close flashes. The transient recorder was operated at a 300 ms pre-trigger mode. The rise time of the broadband antenna system (fast field) for step input pulses was less than 30 ns, while the decaying time constant was set to approximately 15 ms.

3. Result and discussion

3.1. Characteristics of the PB pulse train

The PB pulse trains preceding negative first return strokes were recorded from five convective thunderstorms in Johor, Malaysia in 2009 (on 21, 23, 26, 29, and 30 May). In the data set obtained in Malaysia, PB pulse trains preceding first return strokes were detectable in 97 out of 100 recorded flashes. Out of these 97 flashes, 88 flashes (91%) were characterized as typical PB pulse trains, with the initial polarity of bipolar pulses being the same as that of return stroke pulses. However in 9 flashes (9%) the initial polarity of bipolar pulses in the train was opposite to that of the succeeding return strokes. Even though the same instrumentation was used, it appeared that the number of detectable PB pulse trains in our study is inconsistent with Gomes et al. (1998). This may be due to the different geographical location specifically by oceanic location. The PB pulse trains preceding the negative first return stroke in Florida were obtained from four thunderstorms in 2009 (on 22, 24, 25, and 29 August). In the Florida data set, all 100 flashes had detectable PB pulse trains and were identified as typical PB pulse trains preceding the negative first return stroke.

We present an analysis of the PB pulse train with the objective of providing a detailed description of the criteria for the identification and selection of the PB pulse train in our data set as mentioned above. The analysis include pulse shape, pulse train duration, individual pulse duration, interpulse duration and 'B, I, L' description (defined by Clarence and Malan, 1957). We performed this analysis specifically for the data set in Malaysia, considering that to date there is no available literature concerning locations in proximity to the equator. Our Florida data set, however, is found to be similar to other findings and available literature as reported by Beasley et al. (1982), Rakov et al. (1996), Nag and Rakov (2008) and Nag and Rakov (2009). The criteria used for the identification of the PB pulse train in the negative cloud-to-ground flash are based on the features described in the introduction by Nag and Rakov (2008). To satisfy the selection set for the PB pulse train in the negative cloud-to-ground lightning flash in our data set, we used the same methodology as reported by Nag and Rakov (2008), and Nag and Rakov (2009). We assumed that any other lightning events, such as hybrid flashes with regular intracloud (IC) discharges occurring prior to the negative cloud-to-ground flash, as

anomalous cases, which are not used in our study. In addition, we also assumed that the pulses in the train are bipolar as reported by many investigators (as described in Introduction). Furthermore, the pulses with peak-to-peak amplitudes should exceed twice that of the average noise level. We considered the pulse as belonging to the pulse train if the separation from the last pulse is less than 2 ms.

The definition of pulse train duration, individual pulse duration, and interpulse duration as described by Nag and Rakov (2008) and Nag and Rakov (2009) are as follows:

- i. Pulse train duration: the time interval between the peaks of the first and last pulses in the train.
- ii. Individual pulse duration: the full width of the pulse.
- iii. Interpulse duration: the time interval between the peaks of two consecutive pulses.

The 'B, I, L' (B: breakdown, I: intermediate and L: leader) description, which is also known as the BIL model as defined by Clarence and Malan (1957) is used to identify the pattern of electric field changes preceding the first negative cloud-to-ground flashes. The BIL model is an important tool for our analysis as it reflects the determination of the pulse train and the interpulse durations. From a total of 97 flashes with detectable PB pulse trains in the data set obtained in Malaysia, 45 flashes (47%) were found to be consistent with the 'B, I, L' form. Fig. 1 shows two examples of typical patterns of electric field changes preceding the first negative cloud-to-ground flashes. In the 'B, I, L' form, 24 (24%) out of 97

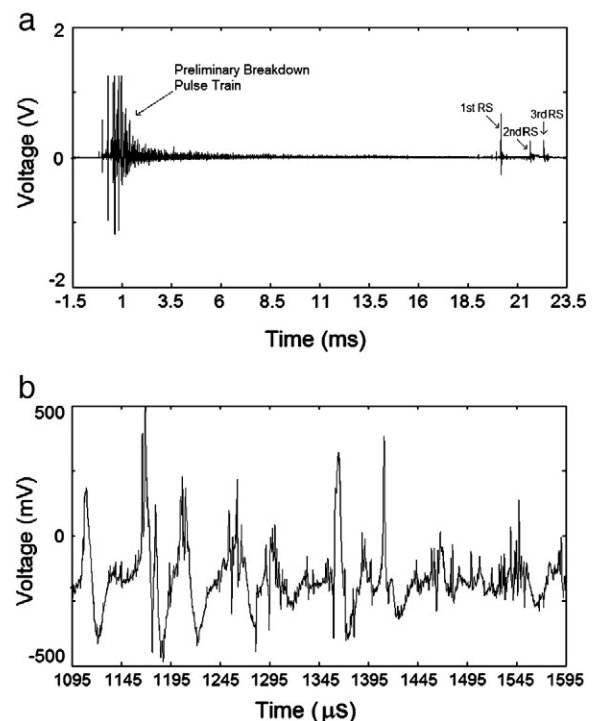


Fig. 2. (a) Close up figure with 25 ms of time frame which was taken from negative cloud-to-ground lightning flash recorded in 26/05/2009 at 05:18:27.580181 (utc). This sample shows a pronounced preliminary breakdown pulse train, intermediate, and step leader that can be fitted to 'B, I, L' form. (b) Close up from (a) with time frame of 500 μ s showing irregularity of pulses and complex shape.

flashes are characterized as regular pulses in the PB pulse train, inside the B section. Another 21 (22%) cases of the 'B, I, L' form were characterized as having irregular pulses with complicated shapes in the PB pulse train inside the B section. The irregularity features of the pulses in the PB pulse train (see Fig. 2b) are found to display small pulses, either unipolar or bipolar, that were superimposed on other distinct bipolar pulses in the train. These features portrayed some confusion in our attempt to recognize the correct type of pulses, as well as the polarity. We also identified 52 flashes (54%) as having the 'B, L' form, suggesting the possibility that the 'I' section might have a duration of zero. The 'B, L' form features are depicted in Fig. 3. The flashes which are profiled in Figs. 2 and 3 were considered as complicated cases, which require complex methods of analysis, especially for parameters such as the pulse train duration, individual pulse duration and interpulse duration. It is for this very reason that we decided to focus our analysis on 24 of the most-known typical flashes

(i.e., consistent with the 'B, I, L' description) which are characterized as regular pulses in the PB pulse trains.

Figs. 4 and 5 show ranges of variations and (vertical bars) of pulse duration and interpulse intervals in individual pulse trains, respectively. Fig. 4 notes that the range of variations and the weighted (by number of pulses in the train) arithmetic mean of pulse durations for all 24 flashes were 1–92 μs and 11 μs . All the pulse trains were found to have minimum pulse durations in the range of 1–2 μs (see Fig. 4). For interpulse intervals, Fig. 5 indicates that the parameter varies from 1 to 1908 μs with the weighted (by number of interpulse intervals in the train) arithmetic mean of 152 μs . A histogram of the total pulse train duration is shown in Fig. 6. Note that the total of pulse train duration varies from 2 to 37 ms. The arithmetic mean and geometric mean of the total duration of pulse trains were 12.3 and 10.1 ms, respectively.

For the comparative study, the available results obtained by Nag and Rakov (2008) and Nag and Rakov (2009) whose

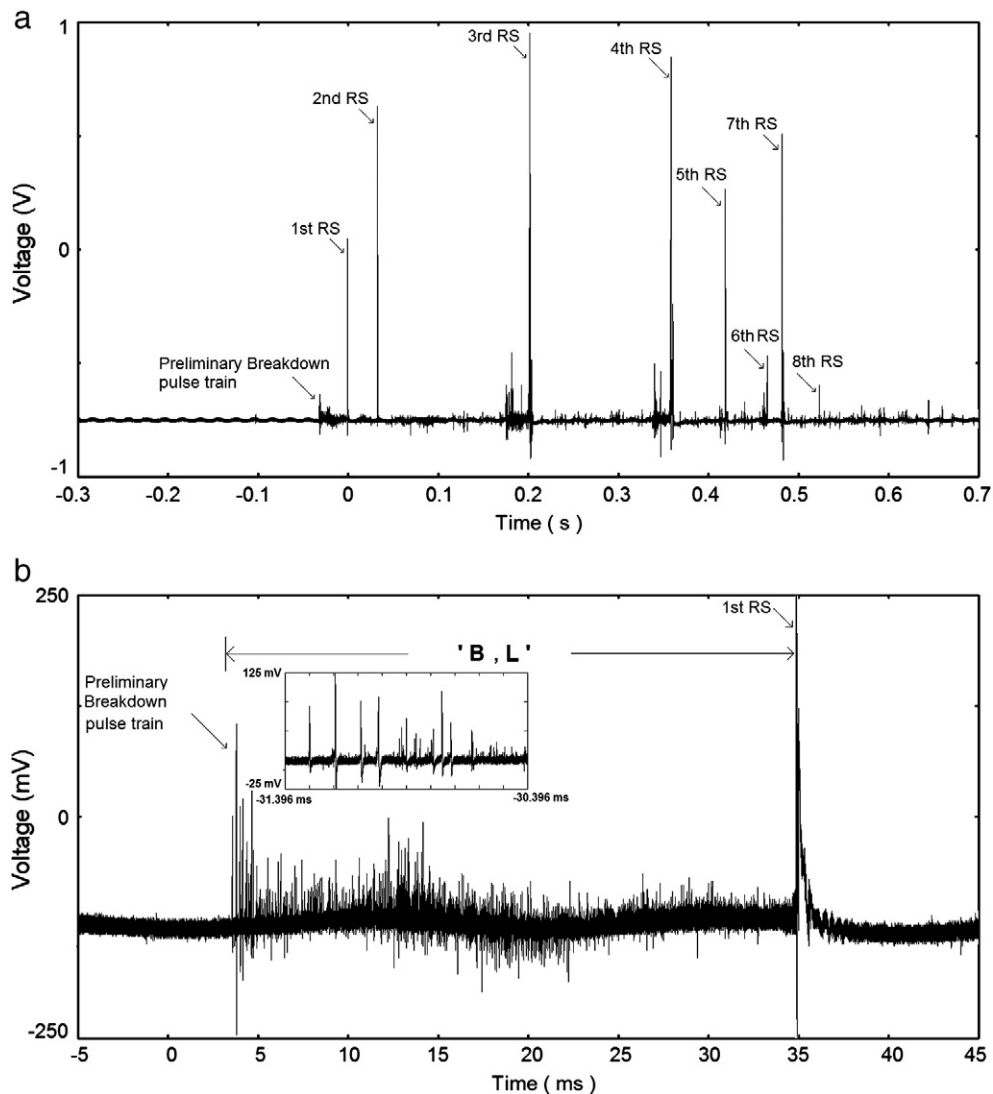


Fig. 3. Electric field record of negative cloud-to-ground lightning flashes showing a pronounced preliminary breakdown pulse train and step leader that can be fitted as 'B, L' description. (a) Recorded in 29/05/2009 at 07:36:04.001174 with 1 s of time frame. (b) Close up from (a) with time frame of 50 ms.

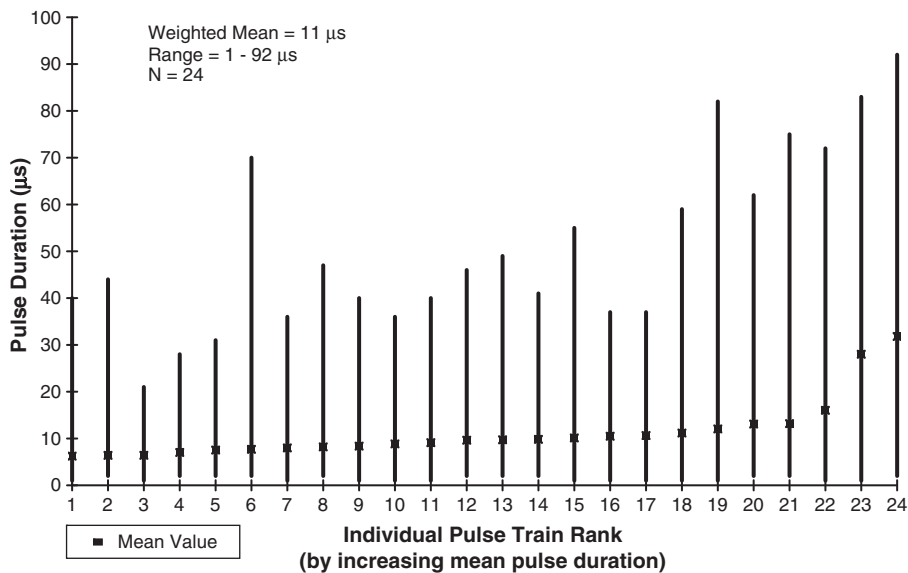


Fig. 4. Ranges of variation (vertical bars) and mean values (square) of pulse duration in individual PB pulse trains.

data set were recorded in Gainesville, Florida are summarized in Table 1. The work of Nag and Rakov (2009) compared the PB pulses in attempted cloud-to-ground leaders noted that the initial polarity of pulses was positive (atmospheric electricity sign convention), which is the same as that of the PB pulses in the negative cloud-to-ground flashes. The weighted arithmetic mean of the interpulse interval obtained by Nag and Rakov (2008) and Nag and Rakov (2009) were 73 μs and 65 μs , respectively. The arithmetic and geometric means of the total duration of the pulse train obtained by Nag and Rakov (2008) were 2.7 ms and 2.3 ms, respectively. Nag and Rakov (2009) found the arithmetic and geometric means of the total duration of the pulse train to be 3.4 ms and 3.2 ms. It is noted that the weighted arithmetic mean of the interpulse interval and the means

(arithmetic and geometric) of the total durations of the pulse trains obtained by Nag and Rakov (2008) and Nag and Rakov (2009) are similar to each other. However, the weighted arithmetic mean of the interpulse interval and the means (arithmetic and geometric) of the total durations of pulse trains from our study were greater than that of the two studies mentioned above by more than a factor of 2 and 3, respectively.

Besides this, Nag and Rakov (2008) on one hand found the weighted arithmetic mean of the pulse duration to be 17 μs which is comparable with our result (see Table 1). On the other hand our result is different from the work of Nag and Rakov (2009). The result of Nag and Rakov (2008) showed the weighted arithmetic mean of the pulse duration associated with the attempted leaders to be greater than the PB

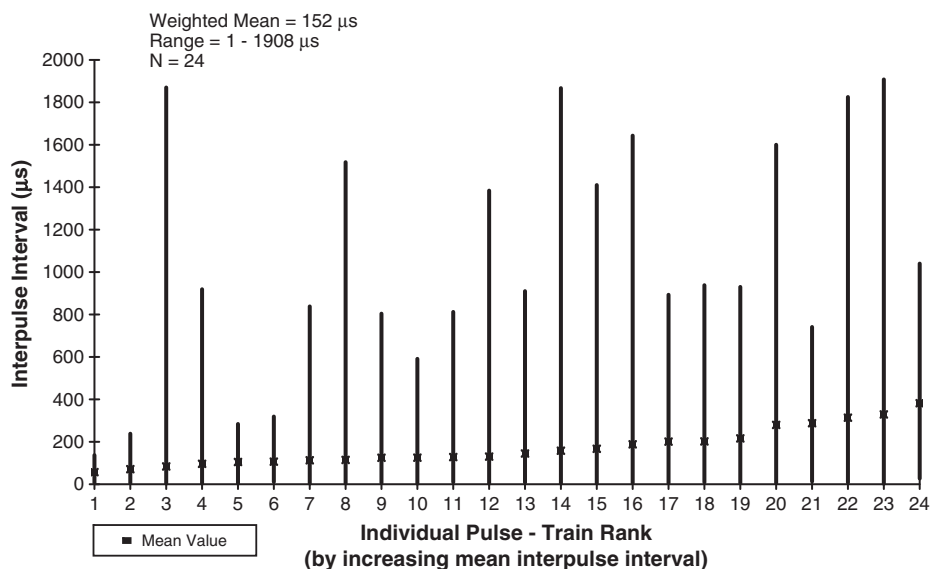


Fig. 5. Ranges of variation (vertical bars) and mean values (square) of interpulse interval in individual PB pulse trains.

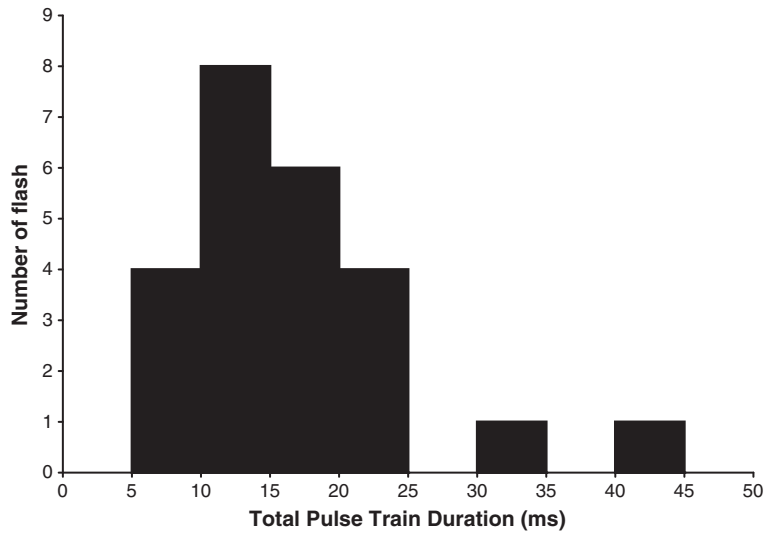


Fig. 6. Histogram of the total duration of PB pulse trains for 24 cloud-to-ground flashes.

pulses in the negative cloud-to-ground flashes (4.8 μ s) in Nag and Rakov (2009) by a factor of 3. From Table 1 the data sets were measured and analyzed using the same methodology. However the different locations played a significant role, indicating differences in characteristics of PB processes. One possible explanation for the differences in the characteristics of PB pulse trains in our study may be due to the differing meteorological conditions, region, and latitude effect. The mean duration of individual pulse still remains less than the lower bound of the 20–40 μ s range of typical durations previously reported by Rakov and Uman (2003) for “classical” PB pulses.

3.2. Relationships between the PB pulse and the first RS

The methodology in this analysis refers to the work of Gomes et al. (1998), Cooray and Jayaratne (2000), Gomes and Cooray (2004), Mäkelä et al. (2008), and Nag and

Rakov (2009). The PB/RS is the amplitude ratio between the maximum peak of the electric field in the PB pulse train and the peak of the RS. The PB–RS separation is defined as the time interval between the maximum peak of electric field in the PB pulse and the peak of the RS. Figs. 7 and 8 depict two PB pulse trains with pulse polarities identical to that of

Table 1 Comparison of PB pulse trains characteristics in Florida and Malaysia.

Parameter	Nag and Rakov (2008), Florida	Nag and Rakov (2009), Florida	This study, Malaysia
<i>Pulse duration</i>			
1. Weighted arithmetic mean (μ s)	17	4.8	11
2. Range (μ s)	1–91	0.5–49	1–92
3. Sample	35	12	24
<i>Interpulse intervals</i>			
1. Weighted arithmetic mean (μ s)	73	65	152
2. Range (μ s)	1–530	0.6–1585	1–1908
3. Sample	35	12	24
<i>Total of pulse train duration</i>			
1. Arithmetic mean (ms)	2.7	3.4	12.3
2. Geometric mean (ms)	2.3	3.2	10.1
3. Range (ms)	0.8–7.9	1.1–5	2–37
4. sample	35	12	24

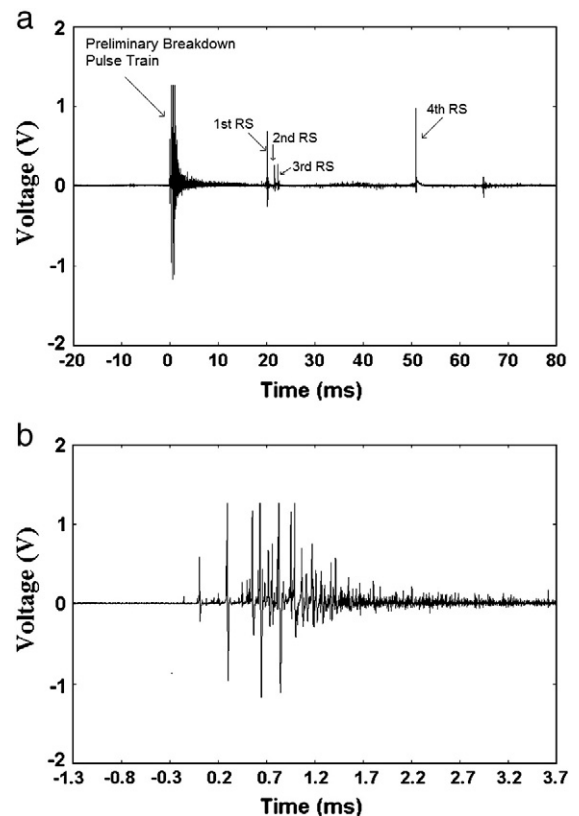


Fig. 7. Highest PB/RS in Malaysia (a) Time frame: 100 ms, (b) time frame: 5 ms.

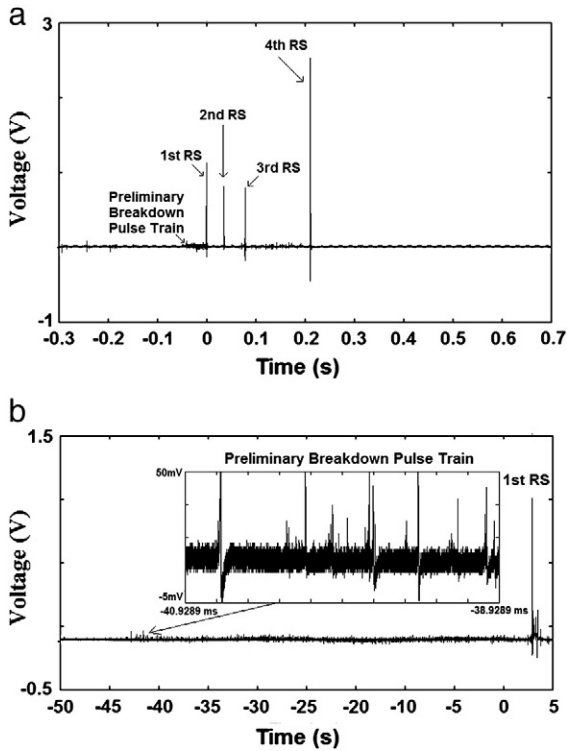


Fig. 8. Lowest PB/RS in Malaysia (a) Time frame: 0.5 s, (b) Time frame: 100 ms.

the return strokes recorded in Malaysia. Fig. 7 shows an event where the amplitude of the largest preliminary breakdown pulse exceeds that of the return stroke. Fig. 8 shows an example where the amplitude of the preliminary breakdown pulses is much smaller than that of the return strokes. In fact, this is the only event that produced the smallest preliminary breakdown pulse train observed in this study. However, the preliminary breakdown pulse activity above the noise level can be clearly observed.

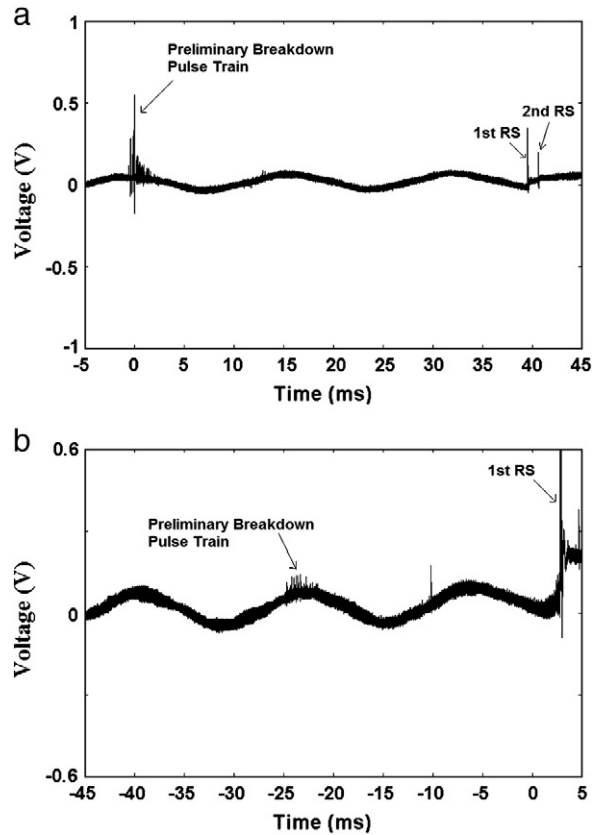


Fig. 10. (a) Highest PB/RS ratio in Florida (time frame: 50 ms), (b) lowest PB/RS ratio in Florida (Time frame: 50 ms).

The distribution of PB/RS ratio of flashes observed in Malaysia is given in Fig. 9. The arithmetic mean, the geometric mean, and the standard deviation of the PB/RS ratio obtained in Malaysia are 27.8%, 14.6%, and 42.2%, respectively. The minimum and maximum values of the ratios observed are 2.6 to 228%, respectively. Fig. 9 shows that there were six

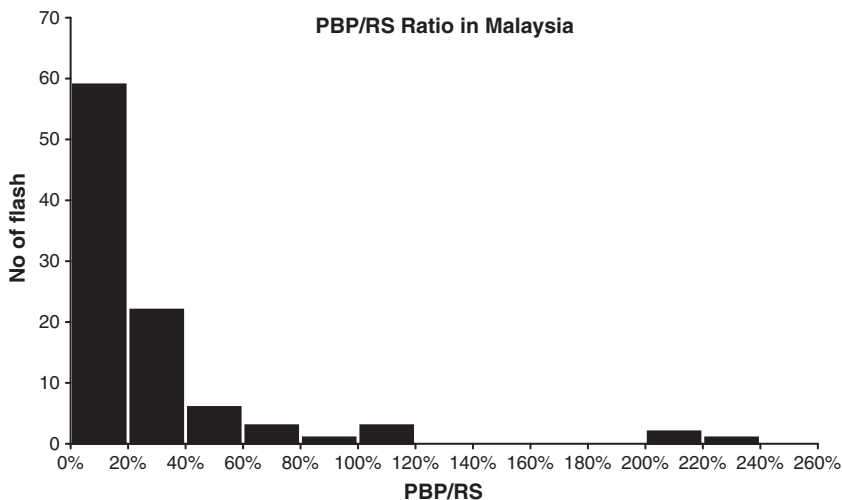


Fig. 9. The distribution of PB/RS ratio in Malaysia.

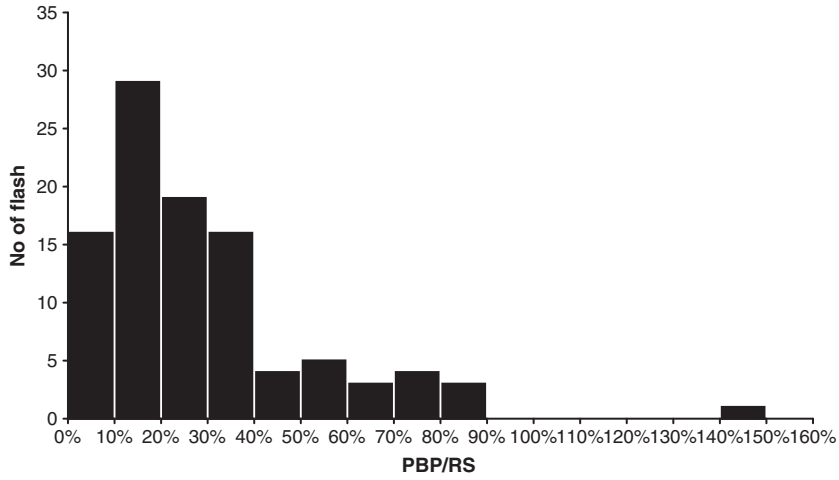


Fig. 11. The distribution of PB/RS ratio in Florida.

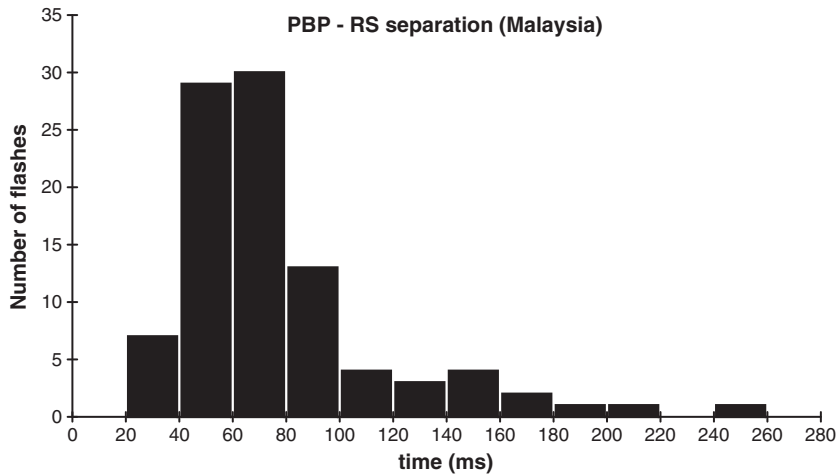


Fig. 12. The distribution of PB-RS separation in Malaysia.

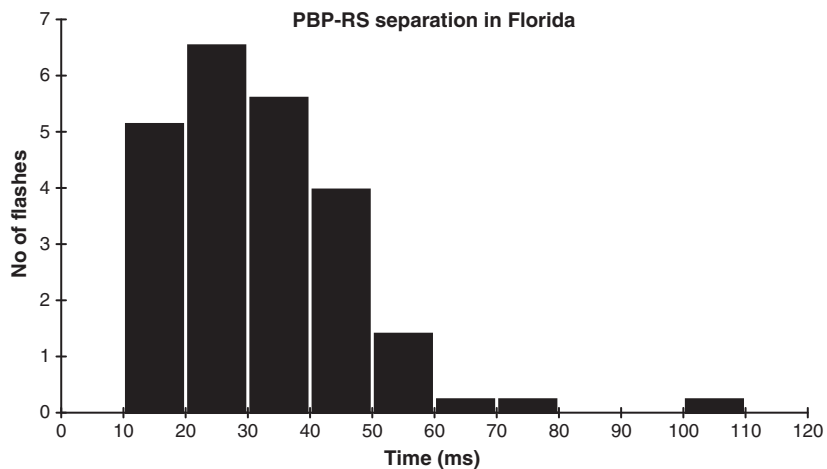


Fig. 13. The distribution of PB-RS separation in Florida.

Table 2
Statistical results for observations made in Malaysia and Florida.

Location	Total no. of flashes	No. of flashes with detect-able PB	PB/RS ratio (%)					N/RS ratio (%)		PB-RS separation (ms)				
			Arith. mean	Geo. mean	Range	Med.	Std. Dev.	Arith. mean	Geo. mean	Arith. mean	Geo. mean	Range	Med.	Std. dev.
Malaysia	100	97	27.8	14.6	2.6–228.1	12.2	42.2	0.7	0.6	57.6	47.2	8.3–227.3	47.4	40
Florida	100	100	29.4	22.3	2.9–149	21.5	23.6	2.3	2	22	17.7	3.3–92.5	22	14.5

Table 3
Comparison with earlier studies.

Location	No. of detectable PB pulse train	PB/RS ratio (%)			PB-RS separation (ms)			Pre-return stroke duration	
		Arith. mean	Geo. mean	Range	Arith. mean	Geo. mean	Range	Arith. mean	Geo. mean
This study (Malaysia) 1° North	97	27.8	14.6	2.6–228.1	57.6	47.2	8.3–227.3	62	51
This study (Florida) 27° North	100	29.4	22.3	2.9–149	22	17.7	3.3–92.5	23	19
Florida (2009) 30° North	59	62	45	16–510	–	–	–	–	–
Finland (2008) 60.4° North	193	61	25	100–610	–	38.5	–	–	–
Sweden (1998) 59.8°	41	101	48.5	8.3–627	13.8	8.7	2–70	–	–
Sri Lanka (1998) 6.9°	9	16.5	14.6	6.2–26.4	11.9	9.8	3.5–2.3	–	–

PB pulse trains, where the amplitude of the largest bipolar pulse exceeded that of the first return. The arithmetic mean and geometric mean of the noise amplitude to the return stroke ratio (N/RS ratio) at our measuring site are 0.7% and 0.6%, respectively. Observe that the minimum PB/RS ratio measured in the study is greater than the mean of N/RS by an approximate factor of 3.7. This indicates that the ambient noise has not affected the results significantly. Two PB pulse trains observed in Florida are depicted in Fig. 10. These pulse trains have the same general features as those observed in Malaysia (Figs. 7 and 8).

The histogram in Fig. 11 provides the distribution of the PB/RS ratio observed in Florida. It was found that the PB/RS ratio in Florida varies from 2.9 to 149%. The arithmetic mean, geometric mean, and standard deviation of the PB/RS ratio are 29.4%, 22.3%, and 23.6%, respectively. The two mean values of the N/RS ratios are 2.3% and 2%. These values are not much higher than the minimum PB/RS ratio, but still lower than the lowest value. We have also evaluated the time

interval between the initiation of the PB pulse trains and the initiation of the return stroke in both regions. The results are shown in Figs. 12 and 13. In Malaysia, the arithmetic mean, geometric mean and standard deviation of this time interval was 57.6, 47.2, and 40 ms, respectively. The minimum and maximum values observed were 8.3 and 227.3 ms, respectively. The corresponding values in Florida were, 22, 17.7, and 14.5 ms, respectively. The maximum value observed was 92.5 ms and the minimum, 3.3 ms. The results from both countries are summarized in Table 2.

The histograms of the PB/RS ratio from both locations (Figs. 9 and 11) indicate that in both locations the RS amplitude exceeds the PB pulses in more than 90% of the cases. However, there are slight differences in the geometric mean as indicated in Table 2. The geometric mean of the PB/RS ratio in Florida is higher than the Malaysian ratio by a factor of 1.5. Moreover, as tabulated in Table 2, the PB–RS separation in Malaysia is greater than the value obtained in Florida.

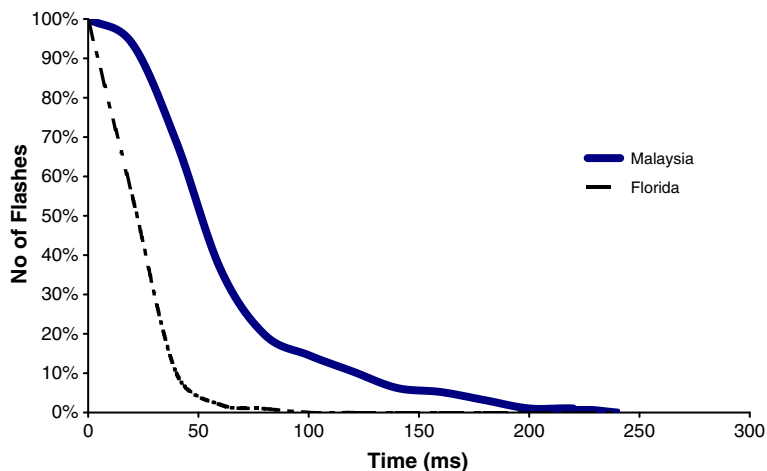


Fig. 14. Cumulative distribution of pre-return stroke duration in Malaysia.

Table 4
Information from radar and satellite.

Date	Data	Arithmetic mean of PBP/RS ratio	Location	Condition
21/05/2009	5	54%	Not available	–
23/05/2009	22	15.8%	Not available	–
26/05/2009	23	51.2%	Overseas, south west (0.74°,103°.12)	Surrounding over sea, some parts of small islands close to Sumatra, distance: 30–80 km
29/05/2009	38	16.7%	Overland, north west	Large isolated thunderstorms approximately 10 km radius, distance: 5–25 km
30/05/2009	11	27.7%	(1.9°,10°) Over land and over sea southwest (1.26°,103°.38) and northeast (1.97°, 104°.14)	Scattered thunderstorms, Location: 20–30 km to the southwest (overseas and overland) and 70–100 km to the northeast (overseas)

In this analysis, we have defined the pre-return stroke duration as the time interval between the first detectable pulse in the PB pulse train and the peak of the return stroke pulse. In Table 3, note that the arithmetic mean, geometric mean of the pre-return stroke durations obtained in Malaysia are 62 ms and 51 ms, respectively, with individual values lying in the range of 9 to 230 ms. The arithmetic mean and geometric mean of pre-return stroke obtained in Florida are 23 ms and 19 ms, while the minimum is 4 ms and the maximum is 93 ms.

Observe that the average value measured in Malaysia is twice the value observed in Florida. The cumulative distributions of the pre-return stroke duration from Malaysia and Florida data are given in Fig. 14. The application of a Student's *t*-test to the two distributions in Fig. 14 indicates that there is less than a 0.1% (0.013%) probability that these two distributions had a common parent distribution. Furthermore the Student's *t*-test is significantly supported our results in Section 3.1, concluded that the characteristics of PB pulses trains in Malaysia and Florida are not similar to each other (see Table 1).

We summarized and compared the results obtained earlier by Gomes et al. (1998) and Mäkelä et al. (2008) and Nag and Rakov (2009) in Table 3. Note that the observations in temperate regions such as in Sweden (59.8°N) and Finland (60.4°N) indicate that the means of the PB/RS ratio are relatively high in higher latitudes. The results reported by Nag and Rakov (2009) in Florida (30°N) also similar to that of two studies. However, as the latitude decreases or as we move closer to equatorial region, the mean of the PB/RS ratio also decreases. It is fair to note that the number of observations that were reported by Gomes et al. (1998) is rather small (9) and this could affect the statistical data. We also found that the PB–RS separation is short at the high latitude region while having long durations in the tropical region. This could be due to the higher altitude of charge centers in tropical regions.

The information concerning the location of thunderstorms was obtained by radar and satellite data provided by the Malaysian Meteorology Department. The data allowed us to identify the location of the most active thunderstorms to an accuracy of a few kilometers during our measurements. We summarized this information in Table 4. Notice that the thunderstorm event on 26/05/2009 generated the highest PB/RS ratio (average 51.2%) while the lowest (average 16.7%) was generated by the thunderstorm on 29/05/2009. We found that the thunderstorm event on 26/05/2009 took

place in the southwest region (0.74°N, 103°.12 W) over the sea and over some parts of small islands close to Sumatra, Indonesia. The distance to that thunderstorm location was between 30 and 80 km. The thunderstorm on 29/05/2009 took place over land. This thunderstorm was a large isolated one, having a radius of approximately 10–15 km. The distance to the thunderstorm from the measuring station was approximately 5 to 25 km, northwest (1.9°N, 10°W).

Another interesting observation of this study is the lightning flashes recorded in Malaysia where the polarity of PB trains is opposite to that of the succeeding return stroke. This phenomenon is shown in Fig. 15 which consists of pulses with positive initial polarity and followed by all negative

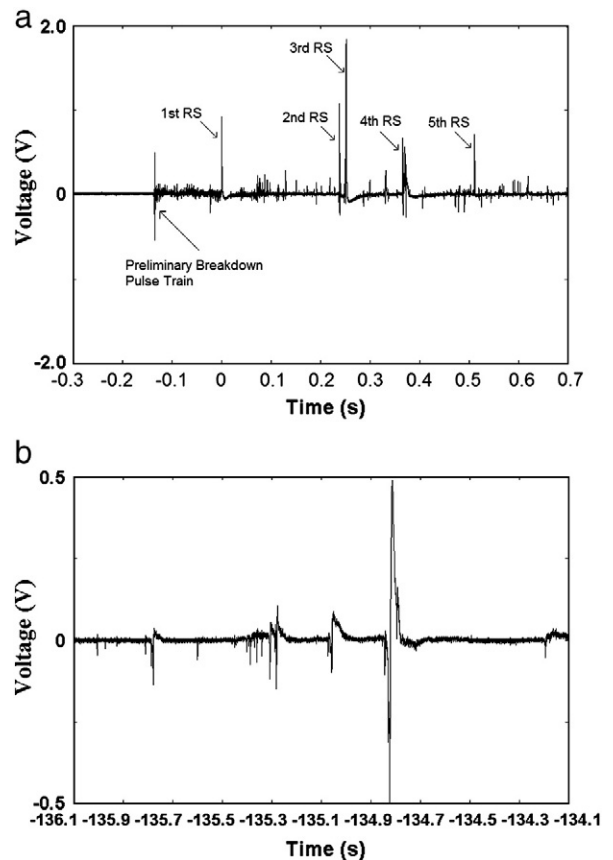


Fig. 15. Opposite polarity of PBP trains to that of the succeeding negative return in Malaysia.

bipolar pulses. We noticed that these types of PB trains have the highest pre-return stroke durations and these duration vary (in 9 cases) from 79 to 230 ms. The occurrence of the anomalous polarity PB trains (i.e. negative initial polarity) in the positive lightning flashes have been reported by Gomes and Cooray (2004). We agree with the speculation made by Gomes and Cooray (2004) that the PB with the initial polarity being opposite to that of the succeeding return stroke may be caused by a breakdown between the main charge centers and irregularly-located charged regions or screening layers.

4. Conclusions

The relationships between the preliminary breakdown pulse and the first return stroke electric fields have been analyzed using high resolution data recorded from Malaysian and Florida thunderstorms. The statistics obtained from our data (Malaysia and Florida) and those obtained earlier in Sri Lanka, Sweden, Finland and Florida, show that the strength of the ground-flash-initiation breakdown process in the cloud, measured with respect to the peak radiation field of the resulting return stroke, is larger at high latitudes compared to that of the tropical regions. The characteristics of preliminary breakdown pulse trains in the negative cloud-to-ground flashes observed in Malaysia have been summarized in Table 1. We found the duration for the initiation preliminary breakdown processes in negative cloud-to-ground flashes in Malaysia is three times greater than in Florida. From our observations in Malaysia, we found that there are differences between flashes that occur over the land and over the sea. However, further investigations addressing the effects of thunderstorms over the land and over the sea is required to speculate regarding the initiation process of cloud to ground flash. The phenomenon of opposite polarity of the PB pulse to that of the succeeding return stroke still remains an open question.

Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.atmosres.2012.01.012. These data include Google maps of the most important areas described in this article.

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