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Temporal analysis on pulse train of lightning discharge observed in Malacca, Malaysia

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Abstract

A few significant studies discovered that a pulse train tends to initiate subsequent return stroke in the same way that a preliminary breakdown pulse activates the first return stroke. This paper presents pulse train characteristics in the lightning waveform obtained in Malacca, Malaysia. This study employed 930 pulse train samples divided into twelve groups. Most of the trains are Type IX, i.e., the chaotic pulse train superimposed on the dart leader, accounting for 38% of the samples. There are only 0.8% of Type VI observed in this study. These fewest trains are with regular pulses preceding chaotic pulses without being separated in time. The majority of the pulse train occurred between the first return stroke and the first subsequent return stroke, i.e., 39% of the samples. Averagely, the pulse train time duration was 653 µs, and the separation time between pulse train and subsequent return stroke was 25 ms. There was a 99.8% chance that a pulse train would initiate subsequent return stroke. This study revealed that the pulse train and subsequent return stroke separation mean value was decreasing with stroke order. This pattern of pulse train occurrences in the lightning waveform can be manipulated in the lightning monitoring system.

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Keywords: Cloud to ground lightning; Chaotic pulse train; Regular pulse train; Parallel plate antenna; Lightning electrical field; Lightning characteristics

1. Introduction

In the lightning research, Weidman [1] was the first to discover the chaotic pulse train (CPT). It is a train of electromagnetic field radiation pulses that occur with or without any return strokes, but they were typically captured immediately before subsequent return strokes (SRS) [2–4]. CPT appear a few milliseconds to several tens of milliseconds before strokes [3,5]. The individual train duration usually lasts for a few hundred microseconds range [3–5]. It is common in the negative cloud to ground lightning waveform as observed by many researchers.

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In Guangzhou, 75.2% of the lightning was accompanied by CPT events [6], while in Malaysia, about 85% cloud to ground lightning flashes were found to have CPT [7]. More studies revealed that less than 50% of SRS were associated with CPT. In north-central Florida, Hill et al. [8] found that 48% of the SRS waveforms exhibited CPT in lightning signals. In 2011, a similar trend was observed in China, whereby 48% of SRS were preceded by a CPT, with an average train duration of 472 μs [4]. Zhang et al. [9] discovered that CPT preceded approximately 44% of SRS when both the optical and electrical fields were recorded concurrently. Gomes et al. [3] reported that CPT is not a usual event in lightning, based on CPT data collected in Sweden, Denmark, and Sri Lanka. Only 25% of the CPT events happened before the SRS signal. Their study suggested that the train duration of CPT was in the range of 400 to 500 μs. Meanwhile, a different study conducted in Sri Lanka found that 30% of subsequent stroke of lightning were associated with CPT [10]. The lightning produced a shorter train duration of the CPT event, an average of 300 μs. However, in rare situations, the pulses can last for more than 500 μs. Furthermore, Hill et al. [8] also discovered four CPT signals followed by return strokes that associated with a long continuing current, a significant charge transfer, and a large peak current. It was evident that a subsequent leader associated with CPT tends to make more significant electric field variations compared to other leaders without chaotic events [4].

Apart from the CPT, another pulse train that is also usually observed just before the next stroke is a regular pulse train (RPT) [11]. As the names imply, RPT consist of regular pattern whereas, CPT are having erratic amplitudes with irregular characteristics. Based on a numerical analysis, Ismail et al. suggested that CPT could be produced by superimposing numbers of RPTs onto each other [5]. Thus, in this study RPT and CPT are generally referring to pulse train (PT) in order to analyze their characteristics. PT research in Malaysia is limited, and most of it focuses on a few states, such as Selangor [12] and Johor [7,13]. Therefore, this study discovers the PT characteristics in a different part of Peninsular Malaysia, specifically in Malacca by conducting a temporal analysis on the PT samples.

2. Measurement

The data used in this study were collected during Malaysia's Transition Monsoon, also known as the intermonsoonal period, in April 2019. The field campaign was launched at the Technology Campus of Technical University of Malaysia, in Melaka. The location is approximately 2°16′36.9″N 102°16′25.5″E, and it is 34 km from the Malacca Straits. To record the electric fields from lightning flashes, a parallel plate antenna integrated with an electronic circuit similar to the one developed by Garvan and Fernando [14] was installed at the site. Many researchers [15–17] had adopted the antenna design, which was claimed to be capable of measuring lightning electric fields up to 100 km away from the antenna. The parallel plate antenna was designed using two circular plates, each with a diameter of 45 cm. The plates were connected in parallel and spaced 3 cm apart. Since the antenna's bottom plate was connected to the ground, the induced voltage on the upper plate from the vertical component of the generated electric field was measured with respect to the ground in this work. The antenna stands 1.5 meters tall and is connected to an electronic circuit by a 60 cm long of RG58 coaxial Bayonet Neill-Concelman (BNC) cable. The cable capacitance, C_c is 100 pF as listed in the datasheet [18]. The output signal of the circuit was fed into a 12-bit LeCroy High Definition Oscilloscope with a maximum bandwidth of 200 MHz via a similar 10 m long coaxial cable. The lightning waveform recorded in the oscilloscope was transmitted through a 160 cm Universal Serial Bus (USB) cable and stored in a personal computer with pre-installed Wavestudio software. The lightning electric field signal captured by the antenna was recorded at a sampling rate of 12.5 MS/s for a total waveform duration of two seconds.

In a few literatures [7,19], the pulse train was described as a microsecond waveform. Thus, a fast field circuit, which can examine portions of the lightning discharge on a faster (microsecond) time scale, such as the pulse train, is used to capture the waveform. To obtain an accurate measurement of the fast electric field, the electronic circuitry should be of sufficient precision to achieve meaningful values for the amplitude and rise time [20,21]. This can be achieved by maintaining a reasonable decay time for the resistor–capacitor (RC) circuit in the fast field circuit. The decay time of the RC circuit used in this work is 16.2 ms, which is sufficient to record the correct microsecond signatures of the pulse train. Additionally, a buffer circuit is also required between the antenna and the oscilloscope due to the mismatch between the antenna's output impedance and the oscilloscope's input impedance. If the induced voltage on the antenna exceeds the permissible limit, the oscilloscope may be destroyed A buffer offers a very high input impedance and low output impedance that protect the oscilloscope against the risk of overvoltage [22]. Hence, an MSK0033 buffer was used for the measurement setup in Melaka. The input impedance is 10^{12} Ω and output impedance is 6 Ω [23]. Wavestudio V9 software was used to analyze the PT samples in order to identify the type and measure the temporal features.

3. Types of pulse train

CPT and RPT are normally observed between return strokes, either alone or superimposed with a dart leader [13]. The term 'superimpose' refers to the fact that the transition phase of PT to dart leader is hard to identify. PT was associated with a dart-stepped leader in Type 1, whereas PT alone was in Type 2 as reported by Wooi et al. [13]. In 2017, Ismail [24] classified these events into ten categories, from Type A to Type J. Significantly, this study found two more PT types that expanded Wooi et al. and Ismail's work. The two new types of PT are Type XI and Type XII; Type XI is for CPT preceding RPT without being separated in time and superimposed on the dart leader, whereas Type XII is when RPT preceding CPT without being separated in time and superimposed on the dart leader. Following that, the PT types were rearranged to fit Type 1 and Type 2. The list of the PT categories is tabulated in Table 1.

Table 1. Types of pulse train adopted in this study.

PT type based on Wooi et al. [13]	PT type based on Ismail et al. [24]	PT type in this study	PT details
2	A	I	RPT preceding CPT and separated in time
	B	II	CPT preceding RPT and separated in time
	C	III	RPT without CPT
	D	IV	CPT without RPT
	G	V	CPT preceding RPT without being separated in time
	H	VI	RPT preceding CPT without being separated in time
	I	VII	CPT appearing in the middle of RPT without any time separation
	J	VIII	RPT appearing in the middle of CPT without any time separation
1	E	IX	CPT superimposed on the dart leader
	F	X	RPT superimposed on the dart leader
		XI	CPT preceding RPT without being separated in time, superimposed on the dart leader
		XII	RPT preceding CPT without being separated in time, superimposed on the dart leader

From 838 flashes captured in Malacca, 47% of the total consist of PT events, and this finding is comparable to those done by Lan et al. [4] and Hill et al. [8]. From all the flashes, there were 930 samples of PT events that occurred in various types. Of most samples, 38% were from Type IX, which is CPT superimposed on the dart leader. The least common type of PT event was Type VI, in which the RPT preceded the CPT without being separated in time, accounting for only 0.8% of all PT events. As mentioned earlier, PT events typically occur before SRS. However, in this study, two PT samples (Sample 1 and Sample 2) from Type 2 burst after FRS without followed by any SRS. Both Samples 1 and 2 came from different types of PT, which were Type III and Type V as shown in Appendices A and B respectively. Only 0.2% of the sample used in this study was not followed by SRS, indicating that 99.8% of the PT sample initiated an SRS event.

4. Characteristics of pulse train

The majority of the PT events observed in this study were superimposed on the dart leader, i.e., the PT Type 1 (Table 2). The type contains approximately 58% of the samples examined. This study supports the findings of Gomes et al. [4] and Zhang et al. [9], who recorded 77% and 65% of PT Type 1 in their samples, respectively. On the contrary, Ismail et al. [24] observed only 12%, whereas Wooi et al. [13] reported 40% of PT Type 1 in their data. Table 2 also presents the PT characteristics, including PT total duration (TD_{PT}) and the separation time between PT and SRS (ST_{PT-SRS}). As shown in Fig. 1, TD_{PT} is the time interval between significant pulse activity regions at the beginning and end of a train. This study revealed that Type 2 is longer than Type 1 with an average TD_{PT} of 668 μs and 634 μs, respectively. Regardless of the type, the average TD_{PT} measured in this study is 653 μs, which was longer compared to the other four studies listed in Table 2. The value was approximately one to three times longer than the results obtained by Zhang, Gomes, and Wooi, as well as ten times longer than Ismail's result. (Table 2). However, our finding agrees with Makela et al. [10] that TD_{PT} can exceed 500 μs. In a different study, Ahmad et al. [7] reported that the most prolonged time duration of the PT could be up to 2 ms. This study discovered significantly longer TD_{PT}, which can last up to 4 ms. Furthermore, the time interval between ST_{PT-SRS} is a crucial

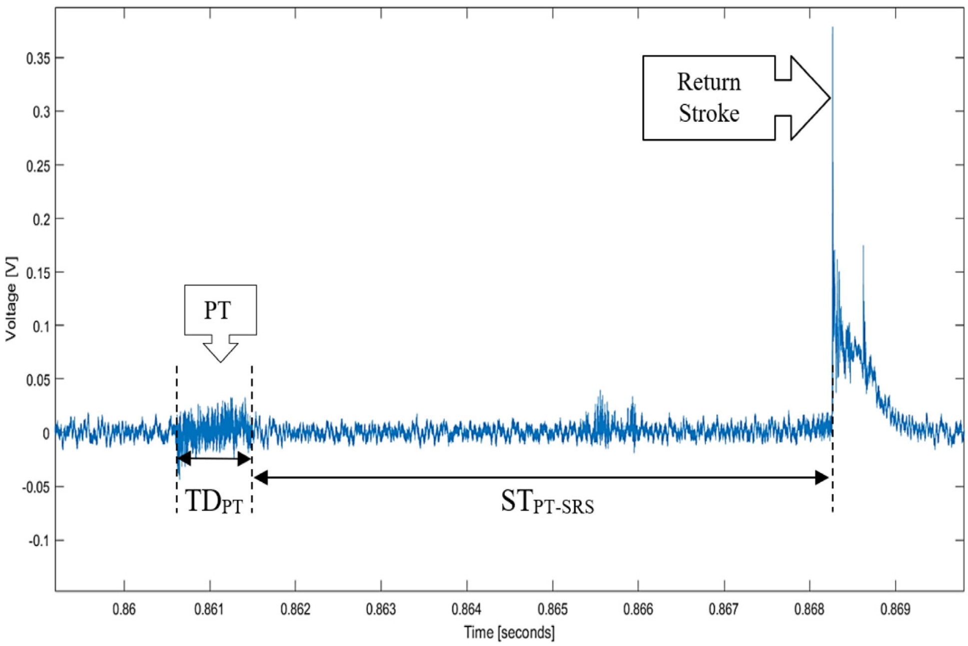

Fig. 1. Measurement of TD_{PT} and ST_{PT-SRS}.

Table 2. Characteristics of the pulse train.

Author	Percentage of PT Type 1 (%)	Percentage of PT Type 2 (%)	Mean PT_{TD} (µs)	Mean ST_{PT-SRS} (ms)
This study	58	42	653	25
Gomes et al. [3]	77	23	450	37
Zhang et al. [9]	65	35	596	1.89
Ismail et al. [5]	12	88	70	4
Wooi et al. [13]	40	60	250	–

factor in predicting the subsequent return stroke occurrences. The separation time is measured between the end of the PT and the start of the next SRS (Fig. 1). The average value of ST_{PT-SRS} measured in this study is 25 ms which consistent with the range suggested by Gomes et al. [3] (i.e. 0.35–73 ms). Nevertheless, it is considerably higher than the findings of Zhang et al. [9] and Ismail et al. [5] by the factor of 13.2 and 6.25, respectively (Table 2). Several studies have reported a short separation time between PT and SRS. For example, Hill et al. [8] found that PT events in Florida occurred at least 10 µs before SRS, while in the Shandong province of China, a PT signal within 150 µs was detected before SRS [25].

Another intriguing aspect of PT is its position of occurrence, which refers to the specific spot in the lightning electrical radiation waveform where the PT exists. The majority of PT events in this study occurred between the FRS and the first SRS, accounting for 39% of the PT samples. The trend is consistent with a study done by Ahmad et al. [7] (i.e. 41.1%). Furthermore, Ismail [24] reported that 62% of PT events applied in the samples occurred primarily in a similar position. This research reveals that 23% of the PT data took place between the first and the second SRS, and 16% was between the second and the third SRS. Following the third SRS, the remaining PT samples were observed. Three positions that could distinguish PT characteristics are (i) the spot between the FRS and the first SRS, (ii) between the first and the second SRS, and (iii) in between the second and the third SRS. The characteristics were analyzed further and tabulated in Table 3. The TD_{PT} and ST_{PT-SRS} were generated between the FRS and the first SRS are the longest of all. Our finding also revealed that the ST_{PT-SRS} mean value decreasing

Table 3. Characteristic of the pulse train occurred in the three positions.

PT position	Number of sample for TD_{PT}	Mean TD_{PT} (μs)	Number of sample for ST_{PT-SRS}	Mean ST_{PT-SRS} (ms)
Between FRS and first SRS.	360	819.44	166	30.93
Between first SRS and second SRS	215	585.40	84	19.93
Between second SRS and third SRS	150	657.09	48	14.83

with stroke order. In addition, results showed that PT Type IX (CPT superimposed on the dart leader) occurred in all three positions.

5. Conclusion

This study recorded 390 negative clouds to ground lightning flashes associated with PT events and 930 PT samples were analyzed. This study has modified and classified PT into two new types based on the most recent PT types. The additional two types were Type XI and Type XII. Overall, most of the PT fell into the Type IV category (i.e., 38%). There was only 0.8% of Type VI that makes it the least PT type observed in this study. In terms of PT positions, this study agrees with other research, with 39% of the samples occurring between FRS and first SRS. TD_{PT} was found to be significantly longer than other findings from around the world. The pattern is most likely due to a seasonal factor, as the data were collected during Malaysia's Transition Monsoon when there were more thunderstorms and heavier rain. Meanwhile, this research is the first in the lightning literature to discover that the ST_{PT-SRS} mean value decreases with stroke order. Yet, the cause is still unknown at this moment. It could be caused by changes in total charges in the thundercloud, or it could be influenced by changes in cloud base height after the FRS. This is an intriguing gap to be explored in the future for the sake of knowledge enrichment. However, the remarkable findings on PT variations and characteristics in this study have contributed to a better understanding of the pulse in lightning events. The following points could be very much helpful in developing algorithms for lightning monitoring systems:

(i) PT could be interpreted as any regular or irregular PT with varying amplitudes. The average duration of PT was 653 μs and occurred 25 ms before the next SRS.
(ii) The ST_{PT-SRS} mean value showed a tendency to decrease with the stroke order.
(iii) The chances of the PT initiating an SRS event was 99.8%.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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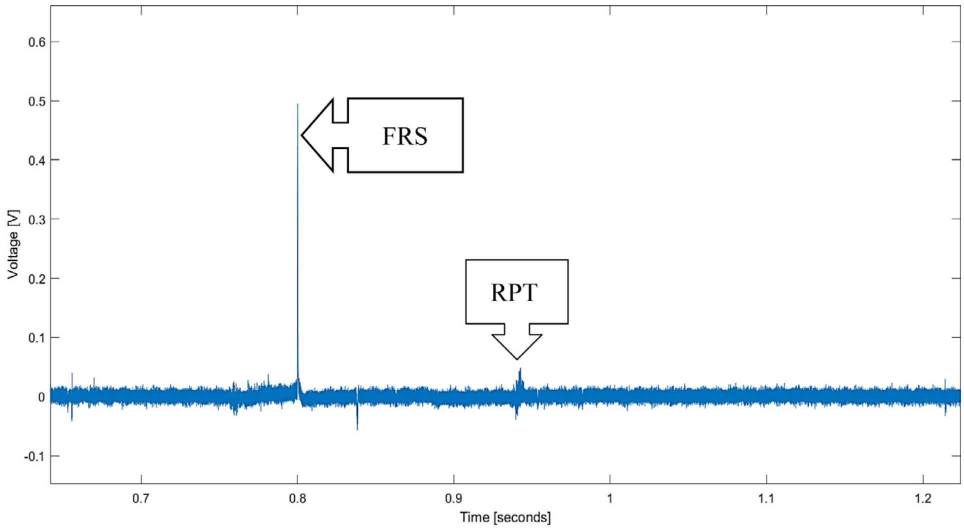
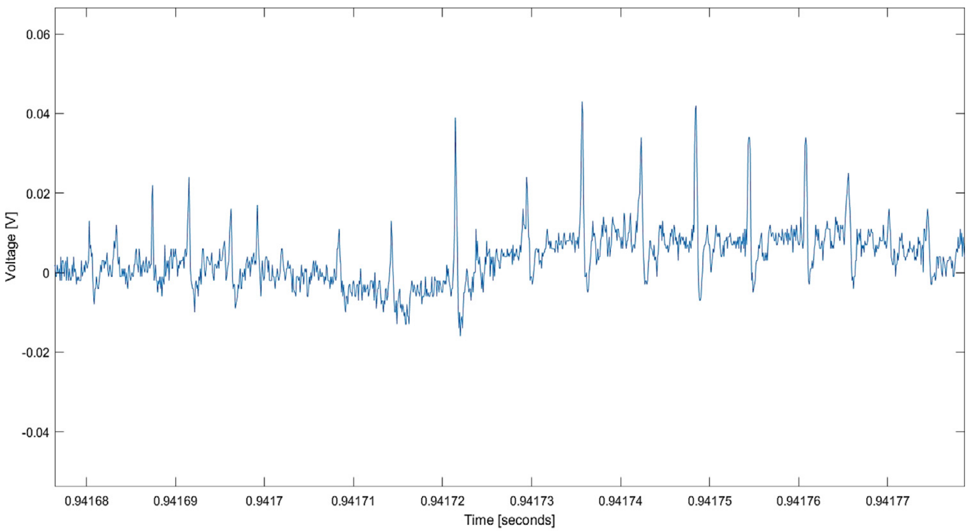
Appendix A. (a) Sample 1 for single flash associated with PT, (b) Type III; RPT without CPT

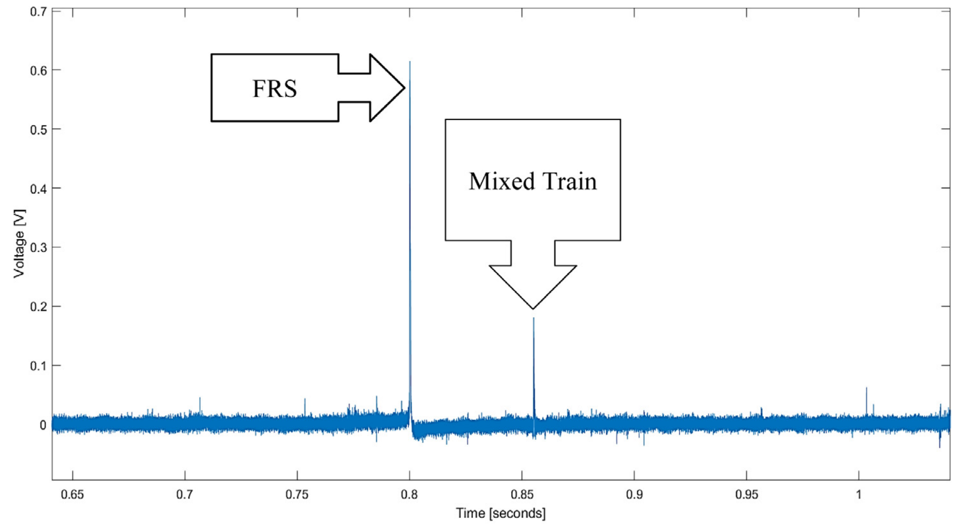


(a)

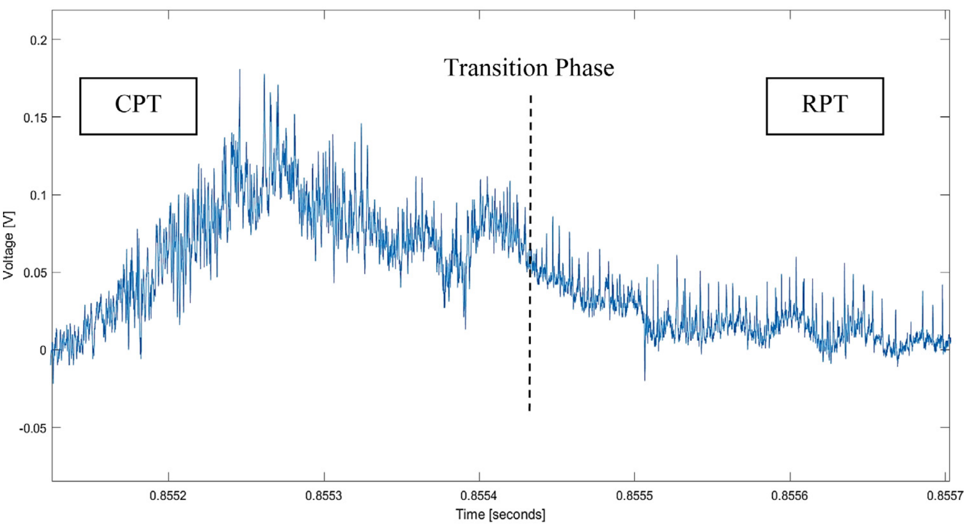


(b)

Appendix B. (a) Sample 2 for single flash associated with PT, (b) Type V; CPT preceding RPT without being separated in time



(a)



(b)

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