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Article

Features of K-changes observed in Sri Lanka in the tropics

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Abstract: General characteristics of K changes together with their fine structure associated with ground flashes in Sri Lanka in the tropics are presented. It is found that on average there are about 2 K changes associated with each return stroke. Analysis of the fine structure of the K changes shows that the K change is a chaotic pulse burst. Some of these chaotic pulse bursts start and the others end as a regular pulse bursts. Sometimes the chaotic part occurs in between two regular pulse bursts. This is in agreement with the recent published results that claim that chaotic pulse bursts are a random superposition of regular pulse bursts. The results show that the small step fields identified in the literature as K changes are the static fields associated with these pulse bursts.

Keywords: lightning flash; return stroke; K change; chaotic pulse train; regular pulse train

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1. Introduction

Kitagawa [1] and Kitagawa and Kobayashi [2] were the first scientists to study what is today is called K-changes. The term K-change is used today to denote relatively small step like field changes that occur in the intervals between and after the return strokes and also during intra-cloud flashes. By analyzing how the polarity of the K-changes vary with distance, they concluded that the field change is produced by a cloud process. Kitagawa and Brook [3] analyzed the signature of these pulses both in cloud and ground flashes in details and concluded that there is no difference between the K-changes produced during cloud and ground flashes. Brook and Kitagawa [4] observed strong emissions within 400 MHz to 1000 MHz during K-changes. Ogawa and Brook [5] proposed that K changes were produced by return stroke like discharges that travel along positive leaders when they encounter negative charged regions. However, the current view is that K changes are recoil negative streamers that propagates along the channels of positive leaders which were cut off from their origin due to channel decay [6].

Rakov et al. 1994 [8], analyzed the micro-scale pulses associated with K-changes. In many K-changes they could not observe any micro-scale pulses. But, in K-changes where the pulses are present the pulse shapes were highly variable and irregular in shape. Usually, these pulses occur at the later stages of the K-changes. In a later study, Rakov et al. [9] observed regular pulse bursts, similar to those observed by Krider et al. [10], in the latter stages of K changes. Interestingly, Krider et al. [10] himself suggested that these bursts are probably associated with K changes.

In this paper, we will provide the statistics concerning the general characteristics of K changes observed in Sri Lanka in the tropics together with the details of the microsecond scale pulses generated during the K-change. Specifically we will demonstrate that the K-change is the static field associated with a chaotic pulse burst.

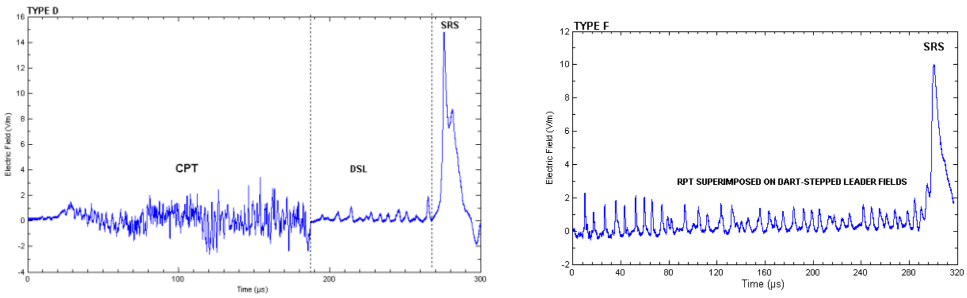
The paper is organized as follows. First we will describe briefly the characteristics of chaotic and regular pulse trains which are essential for our discussion. Next we will show the general characteristics of K changes and finally the microsecond scale pulses associated with them. This is followed by a discussion and conclusions.

2. Chaotic pulse trains and regular pulse trains

The first observation of chaotic pulse trains (CPTs) has been made by Wiedman [11]. He observed that some of the subsequent return strokes were preceded by a pulse train which is irregular in pulse shape, pulse amplitude, pulse width and pulse separation. Gomes et al. [12] demonstrated that CPTs are generated not only in the preliminary breakdown stage of subsequent return strokes but also during the cloud flashes without any connection to ground flashes. Moreover, they were observed to occur during the time interval between subsequent return strokes. Figure 1a shows an example of a CPT that occurred just before a subsequent return stroke.

Regular pulse trains (RPTs) were first reported by Krider et al. [10]. The individual pulses in a RPT are similar to those produced by dart stepped leaders. Krider et al. [10] suggested that these pulse bursts are generated by dart leader type discharge process taking place in the cloud. A typical example of a regular pulse burst that was followed by a subsequent stroke is shown in Figure 1b.

In a detailed study conducted recently by Ismail et al. [13], CPTs and RPTs generated by thunderstorm in Sweden were analyzed in details. Based on their analysis they concluded that CPTs are created by a random superposition of several RPTs generated inside the cloud. Their conclusion is strengthened by the fact that some of the CPTs start as a RPT and some of them end as a RPT. In some cases a RPT appears in the middle of the chaotic pulse train. Based on the suggestion made by Krider et al. [10] that RPTs are generated by dart-stepped leader like discharges inside the cloud, Muzafar et al. [13] concluded that CPTs are created by several dart-stepped leader like discharges propagating inside the cloud. In the sections to follow we will illustrate the connection between the K-changes and the CPTs.



(a) (b)

Figure 1. (a) Chaotic pulse train preceding a subsequent return stroke. (b) Regular pulse train preceding a subsequent return stroke. Adapted from [13].

3. Experimental set up

In this study, electric fields generated by lightning flashes were measured with a flat plate antenna system with a 30 MHz bandwidth, similar to the one used in [14]. Decay time constants of the measuring system was set to 1.0 s for the slow field and 15 ms for the fast field. The signals were recorded by a digitizer with 12-bit resolution. Data was recorded with a 6.4 ns sampling interval allowing 200 ms sample window to be captured from a single trigger. The pre-trigger delay time was set to 60 ms. The bandwidth of the digitizer (PicoScope 6402B) was 250 MHz. The measurements were conducted at the southern coast (5.9360º N, 80.5738 º E) of Sri Lanka during the south - west monsoon period of 2013 (see Figure 2). Most of the flashes occurred over the sea, so the path of propagation was over salt water, except for the last few tens of meters. Hence the propagation effect on the measured fields were minimal. Out of a total of 1106 ground flashes analyzed, ninety eight flashes contained hundred and sixty-five K- changes.

Figure 2. Satellite view of the measuring station (red dot) located few tens of meters from the sea. Adapted from Google maps (10/09/2017).

The slow field antenna system was used to identify the K-changes which occur as small steps in the static field change of the lightning flashes. Selected K-changes were used to measure the pulse duration (T_K), the time interval between the K-change and first return stroke ($T_{RS1\text{-}K}$), time to next return stroke form the K-change ($T_{K\text{-}RS}$), inter K-change interval ($T_{K\text{-}K}$), peak-to-peak voltage of the K-change (V_{PP}) (since the antenna is not calibrated at the site the amplitudes are given in volts) and step voltage change of K-pulse (V_{step}). The definition and procedure of measuring the above mentioned parameters are illustrated in Figure 3 and Figure 4.

Multiple K-changes taking place within a single inter-stroke time interval or after the final subsequent stroke were categorized as "Consecutive K-changes" and if there was only one K-change for a particular flash or within a given inter-stroke time interval, it was categorized as an "Isolated K-change".

4. Results

4.1. Characteristics of K changes

The number of K changes belonging to different categories as observed in the present study is tabulated in Table 1. In our study, out of 1106 flashes only 98 flashes contained clearly distinguishable K-changes. According to the observations, 53 flashes contained consecutive K changes and 45 flashes with isolated K changes. According to Kitagawa Brook [3] approximately three K-changes are associated with a one RS. But in the present study we observed two K-changes per RS as the most frequent value. This differences may have been caused by the difference of geographic locations where the studies were conducted. It is also possible that inadequate sensitivity and sampling rates of the measuring systems used in [3] may have misled the authors of the study to identify other pulse types as K-changes. Figure 3 shows a sample of isolated and consecutive K-changes.

Table 1: Summary of selected K-changes for the analysis.

Total no. of flashes	No. of flashes with K- changes	Total no. of K - changes	No. of flashes with consecutive K -changes.	No. of Consecutive K- changes	No. of isolated K-changes.
1106	98	165	53	120	45

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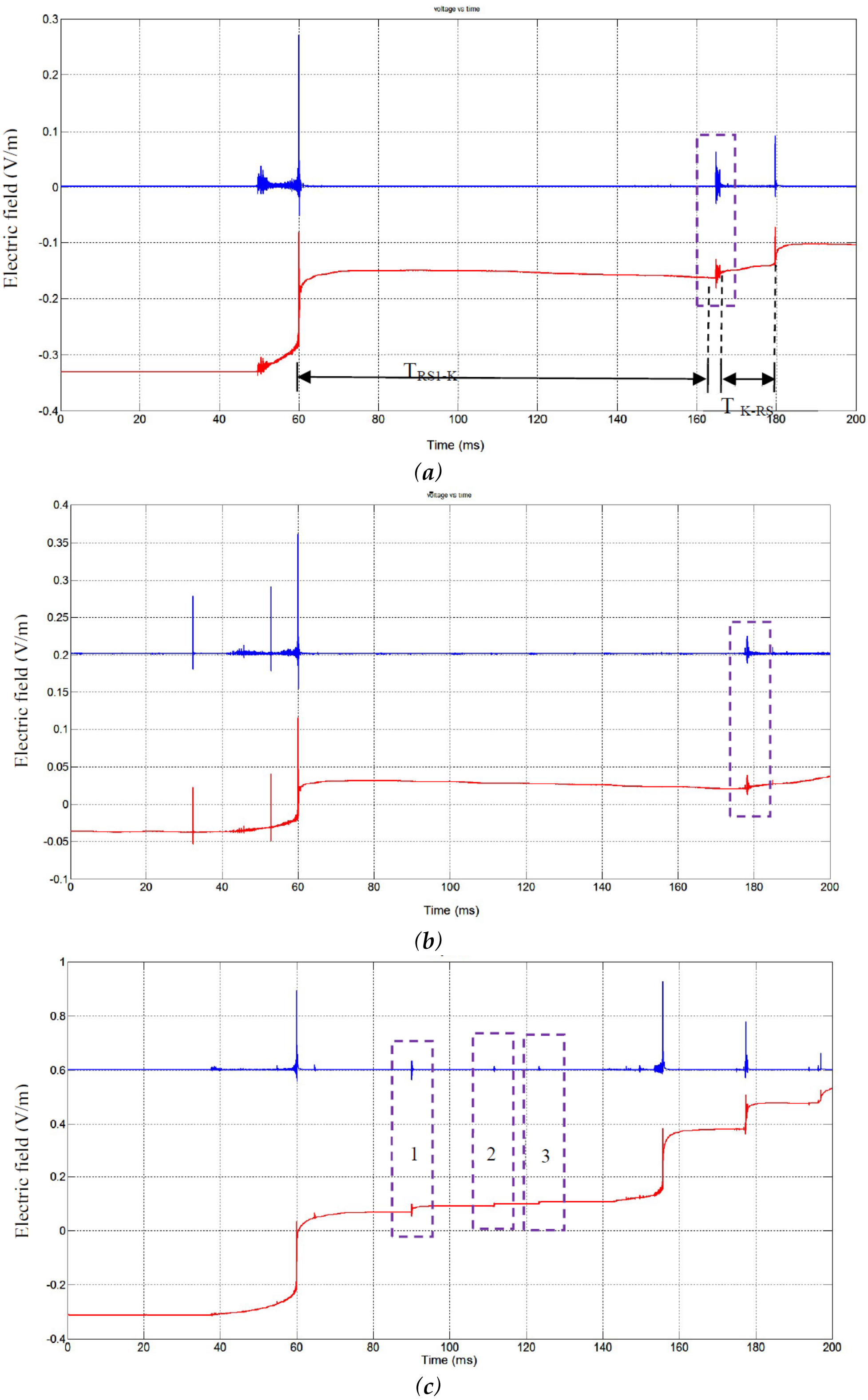

Figure 3. Isolated (K-change (a) between two RS, (b) after RS) and three consecutive K-changes (c) recoded in fast and slow filed antenna systems are presented in blue and red colour. Measured parameters of T_{RS1-K} and T_{K-RS} are presented in (a) above.

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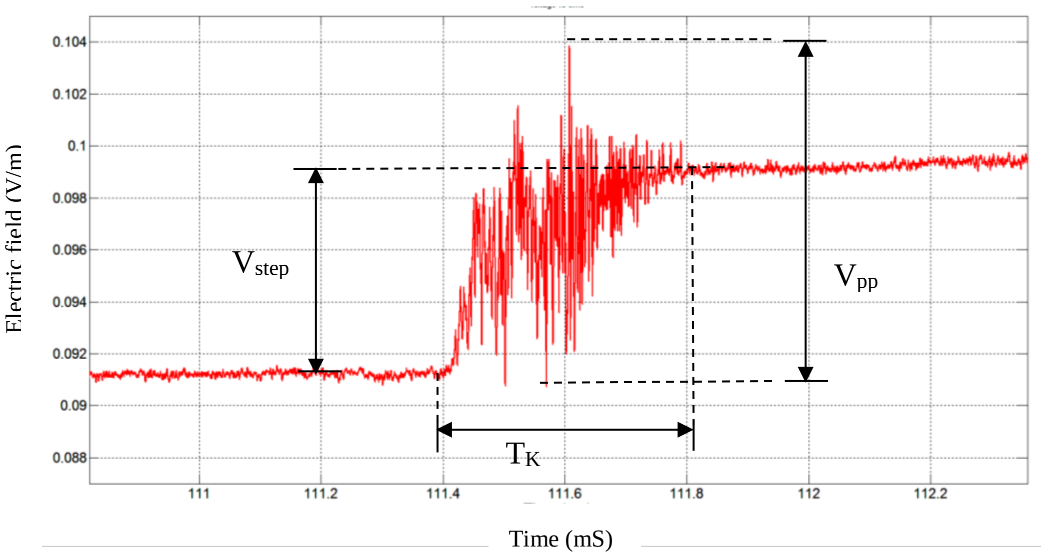

Figure 4. Frist K-change in 3 (c) in expanded scale showing the measured parameters of T_K, V_{step} and V_{pp}.

4.2. Parameters of isolated K-changes

Histogram of measured isolated K-change parameters are presented in Figure 5. As can be seen, the histograms of T_K , V_{PP}, V_{step} and $T_{K\text{-}RS}$ have lognormal distributions but histogram of $T_{R1\text{-}K}$ does not fall into any of the provided distributions in the software package. Summary of the statistical distributions in Figure 5 is given in Table 2. As can be seen, geometric mean of isolated K-change duration was around 350 µs and the most frequent value is 150-250 µs. According to Figure 5(e), isolated K-changes are most likely to occur after 15-25 ms form the first RS.

Table 2. Summery of the statistics for the parameter distributions in Figure 6.

Parameter	Geometric mean	St. deviation	Minimum	Maximum	Most frequent value
T_K (µs)	349.82	300.5	87.8	1599.0	150-250
V_{PP} (mV)	9.81	16.75	1.48	95.33	0-10
V_{step} (mV)	1.43	3.22	0.108	15.430	0-1
$T_{R1\text{-}K}$ (ms)	24.59	27.03	1.93	118.10	15-25
$T_{K\text{-}R2}$ (ms)	14.19	83.7	0.8	533.9	

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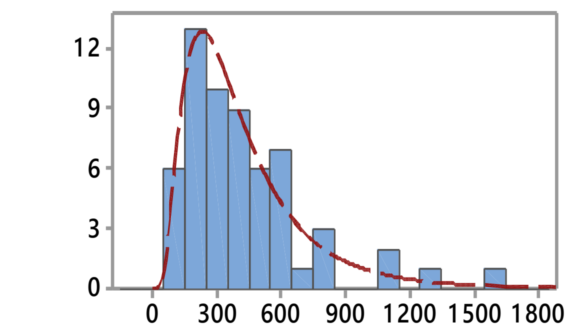
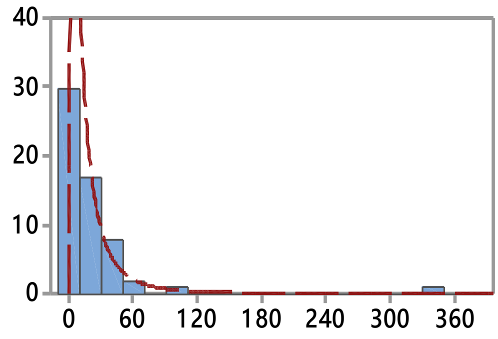
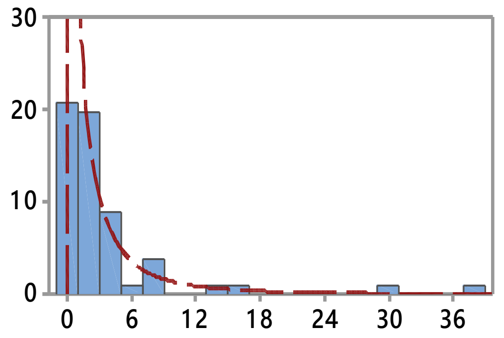


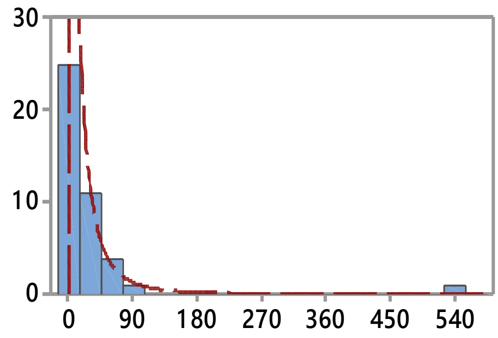
(a) Time duration (ms)



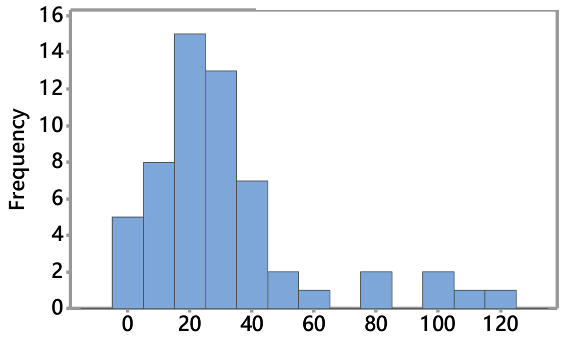
(b) Peak-to-peak voltage (mV)



(c) Step voltage (mV)



(d) Time duration: K-change to last return stroke (ms)



(e) Time duration: 1st return stroke to K-change (ms)

Figure 5. Histogram of the isolate K-change measured parameters, (a) T_K , (b) V_{PP}, (c) V_{step}, (d) $T_{K\text{-}R2}$, (e) $T_{R1\text{-}K}$. Red dotted line represents the lognormal distribution for the histograms in figure (a) to (d). Figure (e) does not fit to any of the distributions by the provided software package.

4.3. Parameters of consecutive K-changes

As given in the Table 1, hundred and twenty consecutive K-changes were found in 53 ground flashes and they were analyzed for T_K , time duration between starting RS to K-change of the consecutive order ($T_{RS\text{-}K}$), time interval between consecutive K-changes ($T_{K\text{-}K}$),time duration between the last K-change of the consecutive order and ending RS ($T_{K\text{-}RS}$), $V_{P\text{-}P}$ and V_{step} .

Histograms in Figure 6 show the distribution of each of the measured parameters and their approximate distributions (without considering the K-change or RS order) provided by the software package. Statistical summary of the distributions in Figure 6 is given in the Table 3. Comparison between statistical values in early studies for consecutive K-changes are presented in Table 4.

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Table 3. Summary of the statistics of the distributions in Figure 6.

Parameter	Average	Geometric mean	St. deviation	Min.	Max.	Frequent value	Distribution
$T_{R1\text{-}K1}$ (ms)	35.98	30.34	21.36	3.46	104.32	15 - 25	Lognormal
T_{K} (μs)	454.8	379.73	292.2	44.6	1650.0	250 - 350	Lognormal
V_{PP} (mV)	19.80	13.35	26.42	2.36	249.40	10 - 30	Lognormal
V_{step} (mV)	5.23	2.95	8.18	0.27	58.19	0 – 7.5	Lognormal
$T_{K\text{-}R}$ (ms)	20.18	12.26	18.49	1.74	71.26	0 - 5	Exponential
$T_{K\text{-}K}$ (ms)	20.27	11.78	26.84	0.67	198.50	10 - 30	Exponential

Table 4. Comparison between statistical values in early studies for consecutive K-changes.

Study	T_{K}		$T_{K\text{-}K}$			Distribution
	Geo.mean (ms)	Frequent value (ms)	Average (ms)	Geo.mean (ms)	Frequent value (ms)	
(Kitagawa & Brook) [3]	-	-	8.5	-	4-6	Lognormal
(Rakov et al.) [8]	0.7	-	-	13	-	-
[15]	-	0.2 - 0.4	-	-	8 -16	-
(Brook & Kitagawa 1964) [4]	-	0.5 -0.75	-	-	-	-
(Thottapillil et al.) [15]	0.7	0.4 - 0.6	-	12.5	10 - 15	-
(Kitagwa 1962) [15]	-	-	-	-	4 - 6	-
(Miranda et al.) [16]	-	-	18.5	12	10 - 16	Lognormal

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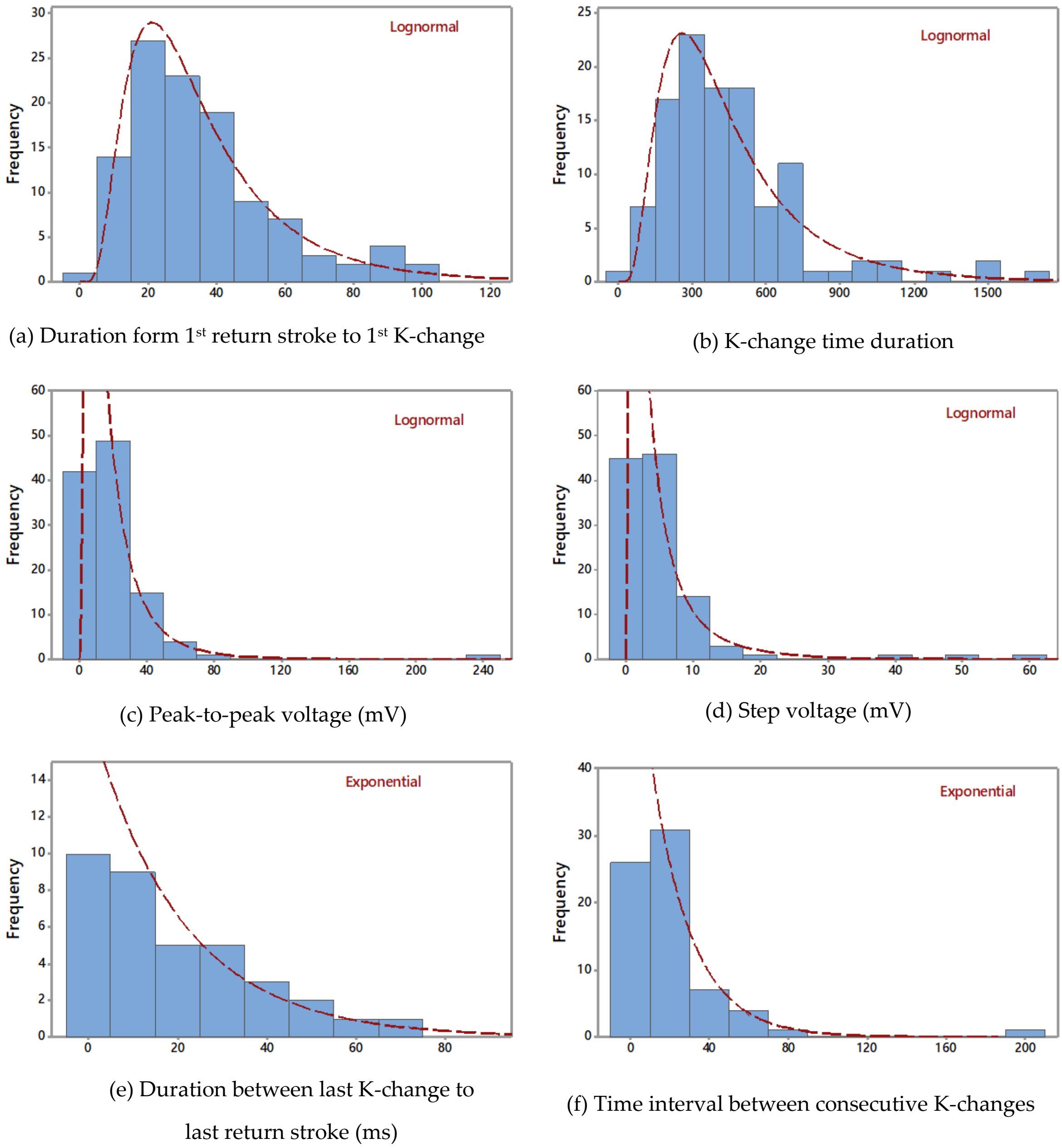

(a) Duration form 1st return stroke to 1st K-change

(b) K-change time duration

(c) Peak-to-peak voltage (mV)

(d) Step voltage (mV)

(e) Duration between last K-change to last return stroke (ms)

(f) Time interval between consecutive K-changes

Figure 6. Histograms of consecutive K-change measured parameters (a) $T_{R1\text{-}K1}$, (b) T_K, (c) V_{PP}, (d) V_{step}, (e) $T_{K\text{-}R}$ and (f) $T_{K\text{-}K}$. Histograms (a) to (d) follows Lognormal distribution and (e) and (f) follows an Exponential distribution which are represented by doted red lines. .

By comparing the data tabulated in Table 3 and Table 4 one can observe that geometric mean of T_K in the present study (0.38 ms) is much less than the value observed by early studies (0.7 ms). Although most frequent T_K value for the present study (0.25 – 0.35 ms) agrees with the value in study [15], reported values by Kitagawa and Brook [3] and Thottapillilet et al. [15] (i.e 0.5 – 0.75 , 0.4 – 0.6 ms) were higher than present values. When comparing $T_{K\text{-}K}$, it can be noticed that average and geometric mean values (20.27 ms, 11.78 ms) of the present study closely agree with those form the study by Miranda et al. [16] (i.e 18.5 ms, 12 ms) although histograms follow different distributions.

4.4. Fine structure of K change electric fields

Appearance of the static field of the K-change pulse in the recording system highly depends on measuring system bandwidth, sensitivity and recording system's sampling rate [2]. Ishikawa noted that, using system decay time constants of 300 μs and 3 ms were not sufficient to recode the field changes without distortion. This was probably why the ramp like K-change appeared as a pulse with a certain rise time and decay time.

Several examples of the typical slow field wave shape of a K-changes from present study are given in Figure 3 and the fine structure associated with it is shown in Figure 4. As can be seen, overall K-changes wave shape shows a characteristic ramp or step like behavior when measured using a slow field antenna. Similar observations have been reported in Figure 2 (c) of study [17] although they have not specifically mentioned about the wave shape.

The fine structure associated with K-changes were studied previously by Rakov et al. [8,9]. However, the time resolution of the present study is much better than the time resolution of the data available to Rakov et al. [7,8] and for this reason more details of the fine structure can be observed here. Our study shows that the overall wave shape of K-changes can be described as ramp change with micro-second scale pulses that start at the beginning and last almost during the total duration of the K change. This is illustrated in Figure 4. Our study shows that the fine structure associated with the K change is a chaotic pulse train (CPT) which starts at the beginning of the K change and continue almost to the end of the K change. Indeed, all the K changes observed in our study are associated with CPTs.

As mentioned previously, Ismail et al. [13] made a detailed analysis of chaotic pulse bursts and observed that they can start or end as regular pulse bursts. Sometimes the regular pulse bursts occur in the middle of the chaotic pulse burst. Our study also shows that the chaotic pulse bursts associated with K changes can either start or end as regular pulse bursts. As in the study reported by Ismail et al. [13] these chaotic pulse bursts can either start or end as regular pulse bursts. Sometimes a regular pulse burst can occur in the middle of the chaotic pulse burst. Few more examples of the chaotic pulse bursts associated with K changes observed in the present study are shown in Figures 7 to 10. Observe that as mentioned before some of the chaotic pulses start as regular pulse burst and the others end as a regular pulse burst.

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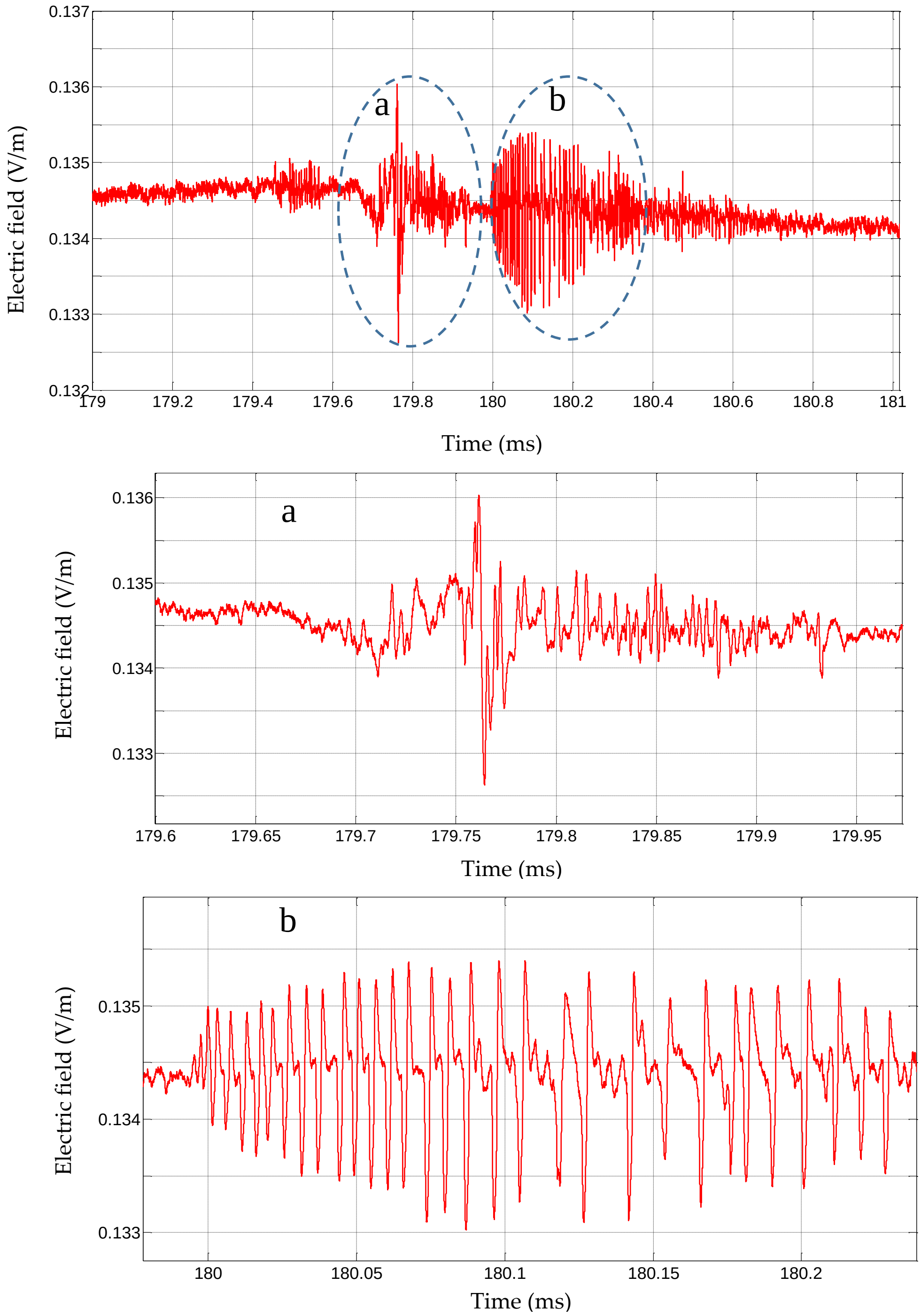

Figure 7. K change staring with chaotic pulse burst and ending with regular pulse burst circled in doted blue lines. Figures (a) and (b) shows the expanded view of chaotic and regular pulse components.

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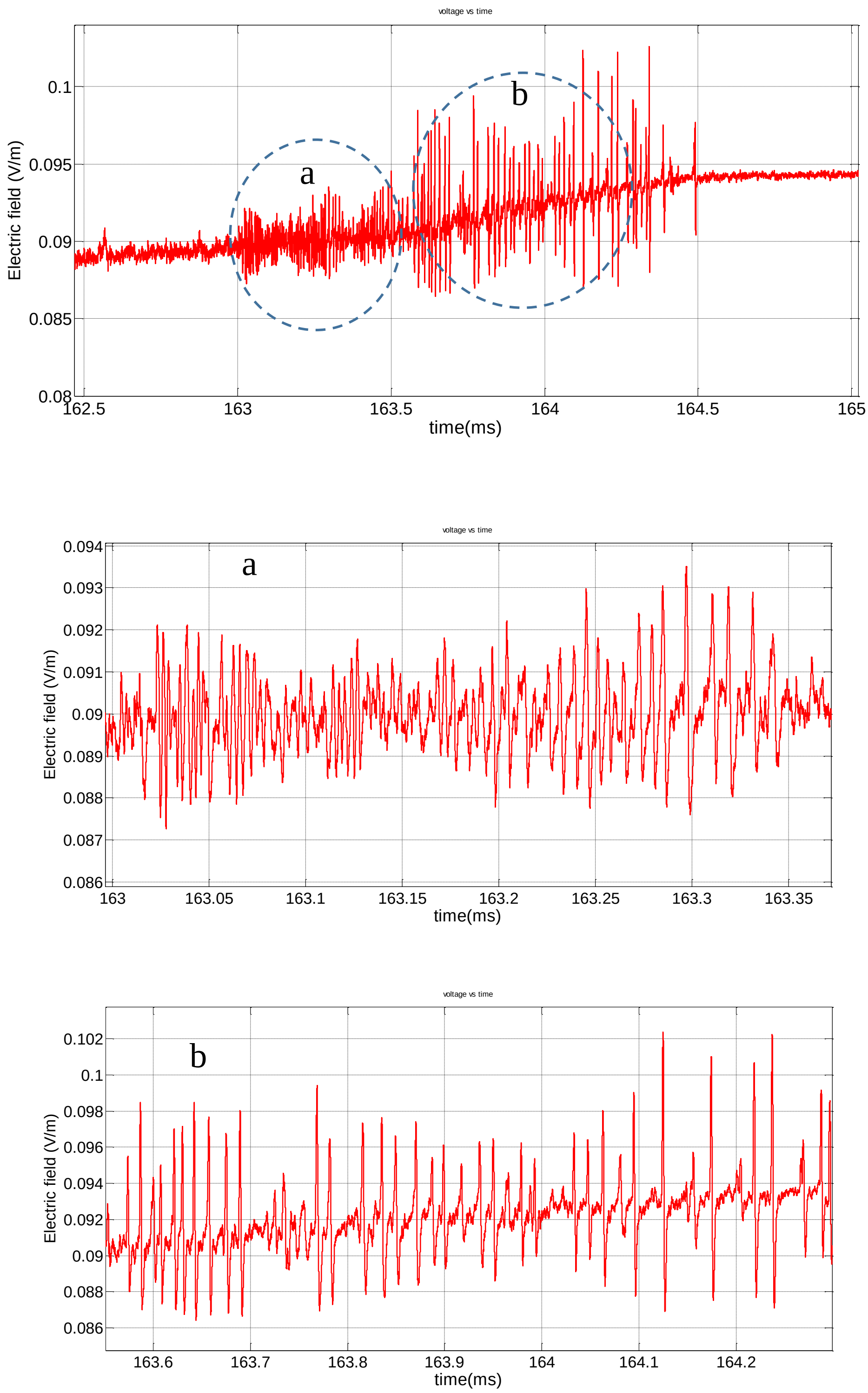

Figure 8. K change staring with chaotic pulse burst and ending with regular pulse burst circled in doted blue lines. Figures (a) and (b) shows the expanded view of chaotic and regular pulse components.

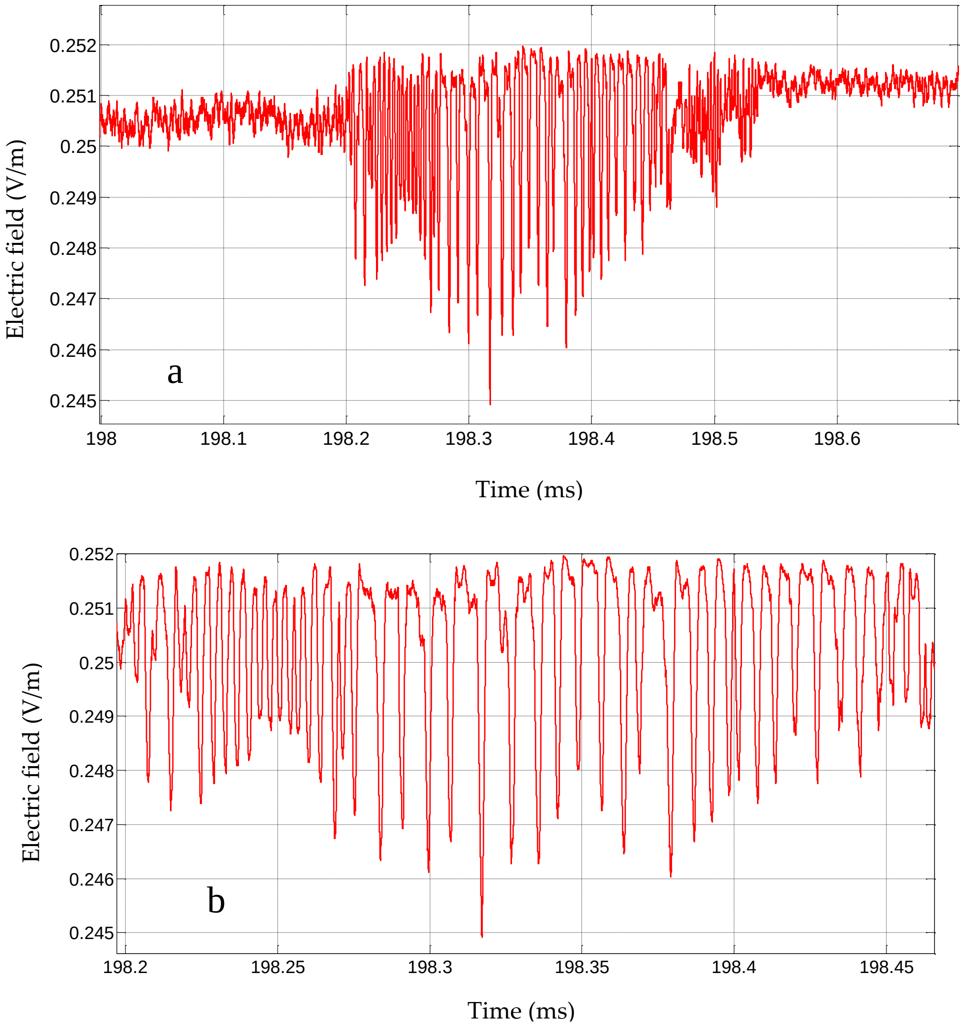

Figure 9. (a) K- change consist of regular pulse trains. (b) Expanded view of the regular pulses.

The results presented here show that the static field change associated with the K change can be regarded as the static field change caused by a chaotic pulse burst. In this respect the K change itself can be considered as the field change produced by a chaotic pulse burst. As mentioned earlier the chaotic pulse bursts were observed first by Weidman [11] to be associated with subsequent return strokes. According to the observations made by Shao et al. [7] there is no physical difference between the processes that initiate subsequent strokes, K changes and M components. All these different processes are associated with negative discharges originating at the ends of the cut off points of positive channels and propagating towards the point of origin of the return strokes [6]. If the discharge happens to make a contact with a partially conducting lightning channel it will lead to a dart leader that will end up as a subsequent stroke. If the discharge make contact with a lightning channel through which a continuing current is flowing it will end up as a M component. If the discharge ends up with a non-conducting lightning channel then it will appear as a K change. Since, K changes are nothing but a chaotic pulse burst there is no surprise that the chaotic pulse bursts are also associated with subsequent strokes. It is of interest in this respect to observe the fine structure associated with M components. The results presented here in combination with Shao's results indicate that the fine structure associated with M components should also consist of chaotic pulse bursts.

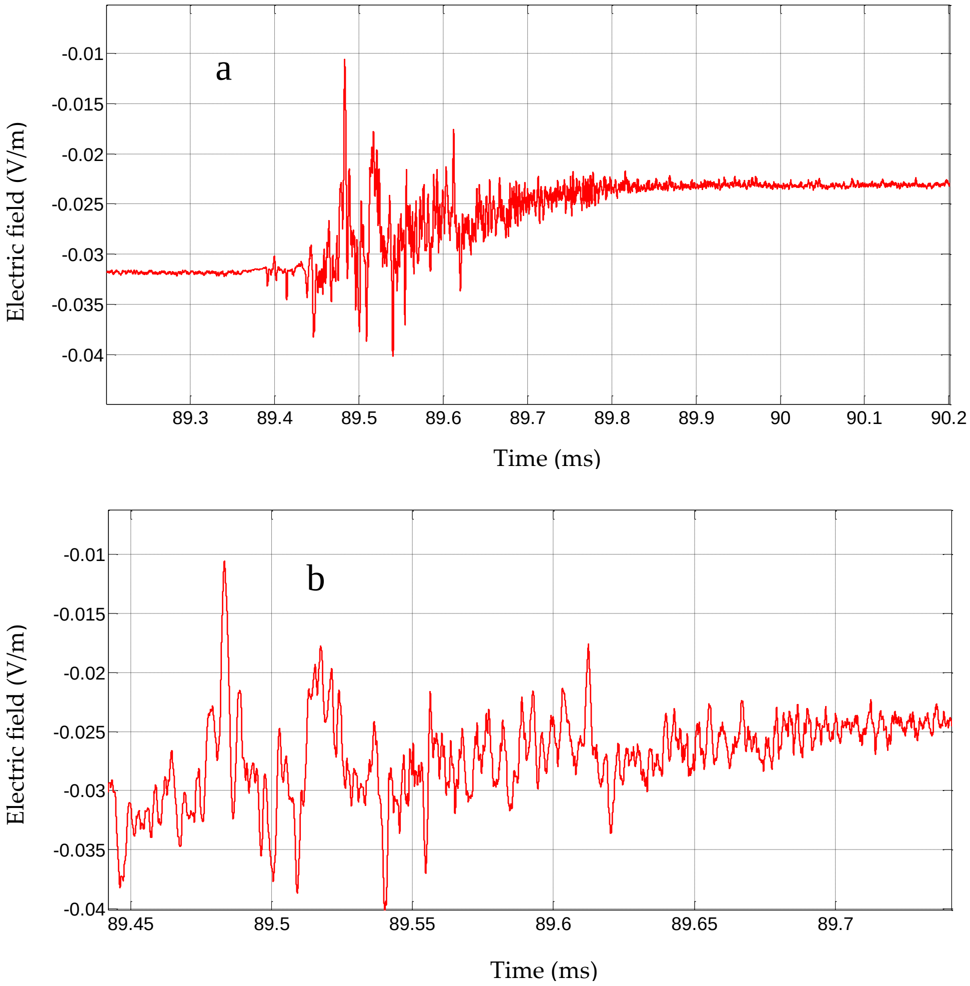

Figure 10. (a) K- change consist of chaotic pulse trains. (b) Expanded view of the chaotic pulses.

4. Conclusion

In this paper we have presented the detailed characteristics of the K changes observed in Sri Lanka located in the tropics. The static electric field associated with the K change can be described as a ramp electric field change. The study shows that the fine structure associated with the K change is a chaotic pulse burst observed previously by lightning researchers. In this respect, one can conclude that the K change as defined in the literature is the static field associated with a chaotic pulse burst.

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Author Contributions: The study was completed with cooperation between all authors. Sankha Nanayakkara

as first author prepared and carried out the experiment, collected the data, analyzed the data, and wrote the draft manuscript. Vernon Cooray contributed to the writing of the manuscript, gave the original idea and checked the validation of measurement. Mahendra Fernando, checked the analyzed data, and contributed with knowledgeable discussions and suggestions. This whole idea came from Mahendra Fernando and Vernon Cooray analysis of the chaotic pulses observed in Sri Lanka. All authors agreed with the submission of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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