CHARACTERISTICS OF CLOUD-TO-GROUND LIGHTNING BASED ON ELECTRIC FIELD MEASUREMENT AND HIGH-SPEED IMAGE OBSERVATION

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DEDICATION

This thesis is dedicated to anyone who seeks knowledge and wisdom beyond Allah's creations. It is also dedicated to my mother, my siblings, my family and many friends for their endless love, support and encouragement.

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ABSTRACT

Malaysia is one of the countries with the highest lightning activities in the world. Thus, lightning monitoring and protection system are vital to safeguarding buildings, communication systems, and electronic equipment throughout the country. Nevertheless, research on the characteristics of lightning in Malaysia is relatively limited, with the majority of published studies focusing solely on West Malaysia. The previous lightning studies were confined to electric fields alone but in this study, however, investigation of electric field characteristics from Cloud-to-Ground (CG) lightning in Malaysia are based on in situ electric field measurement together with high-speed image observation. Field studies were carried out in Malacca (West Malaysia) and Sarawak (East Malaysia) to measure various lightning parameters of negative CG lightning, including the temporal characteristics of the lightning strokes, pulse train (PT), and preliminary breakdown pulse (PBP). Based on the image results, 68% of the captured lightning occurrences exhibited tortuosity, indicating that the typical type of lightning channel in Malaysia is tortuous in behaviour. It was also revealed that 70% of lightning was terminated in a new location. Throughout the investigation, single stroke lightning was the most frequently observed event, accounting for 76% of the recorded lightning images. Averagely, vertical lightning had a longer stroke interval and First Return Stroke (FRS) interval compared to that of tortuous lightning. The PT observed in this study was analysed using the time-domain and frequency-domain. It can be inferred that PT occurrences initiate Subsequent Return Strokes (SRS) since 99.8% of them are found to precede SRS. Interestingly, out of 930 PT samples analysed, this study observed twelve different types of PT. In the time-domain, the PT observed in this work could be interpreted as any regular or irregular PT with varying amplitudes that lasted an average of 653 μs and occurred 25 ms before the next SRS. Additionally, the PT was recorded at a frequency range of 7.7–403.2 kHz and generated an average of 184.6 $(V/m)^2$ peak power, which can reach up to 2170 $(V/m)^2$. The field campaign in Sarawak also recorded other crucial lightning parameters, including normal electric field (E_n), zero-crossing time (T_{ZC}), zero-to-peak rise time (T_{ZP}), and 10–90% rise time (T_{10-90}) of return strokes (RS), which were 40 V/m, 80.1 μs, 7.6 μs, and 4.1 μs, respectively. This study discovered variations in lightning characteristics when striking over sea and land, and its correlation to propagation distance. Furthermore, 52% of the PBP was detected from the data collected in Sarawak. The PBP lasted an average of 3 ms and was 24 ms apart from the FRS. Remarkably, this study successfully carried out the first lightning measurement in East Malaysia as well as discovering more about the characteristics of lightning across Malaysia.

ABSTRAK

Malaysia merupakan antara negara yang mempunyai aktiviti kilat tertinggi di dunia. Oleh itu, sistem pemantauan dan perlindungan kilat sangat penting untuk melindungi bangunan, sistem komunikasi, dan peralatan elektronik di seluruh negara. Namun begitu, kajian tentang ciri-ciri kilat di Malaysia agak terhad, dengan majoriti kajian yang diterbitkan tertumpu kepada Malaysia Barat. Selain itu, kajian kilat tersebut hanya terhad kepada medan elektrik sahaja. Oleh itu, kajian ini dilakukan untuk menyiasat ciri-ciri kilat dari awan ke bumi (CG) di Malaysia berdasarkan pengukuran medan elektrik dan pemerhatian imej berkelajuan tinggi. Kajian lapangan telah dijalankan di Malacca (Malaysia Barat) dan Sarawak (Malaysia Timur) untuk mengukur pelbagai parameter bagi kilat negatif CG, termasuk ciri-ciri masa bagi isyarat kilat, jujukan denyut (PT) dan denyut cetusan awal (PBP). Berdasarkan rakaman imej, 68% kejadian kilat menunjukkan ciri-ciri kecondongan. Terungkap bahawa 70% kilat berakhir di lokasi yang berbeza daripada kilat sebelumnya. Sepanjang penyiasatan, kilat tunggal adalah kejadian yang paling kerap diperhatikan, menyumbang 76% daripada imej kilat yang direkodkan. Berbanding dengan kilat condong, kilat menegak mempunyai sela masa antara satu sama lain dan sela antara kilat pertama (FRS) yang lebih lama. PT yang dicerap dalam kajian ini telah dianalisis dalam domain masa dan domain frekuensi. Dapat disimpulkan bahawa 99.8% kejadian PT telah mencetuskan panahan kilat yang seterusnya (SRS). Menariknya, daripada 930 sampel PT yang dianalisis, kajian ini telah memerhatikan dua belas jenis PT yang berlainan. Dalam domain masa, PT yang telah dikaji dapat ditafsirkan sebagai jujukan denyut berpola atau tidak berpola dengan amplitud yang bervariasi secara purata berdurasi 653 μs dan berlaku 25 ms sebelum SRS berikutnya. Selain itu, PT telah direkodkan pada frekuensi antara 7.7 kHz hingga 403.2 kHz dalam spektrum frekuensi dan menghasilkan purata kuasa puncak 184.6 $(V/m)^2$, yang boleh mencapai hingga 2170 $(V/m)^2$. Parameter-parameter penting FRS termasuk nilai medan elektrik, masa pintasan sifar, masa kenaikan sifar ke puncak dan masa kenaikan 10-90 % telah direkodkan di Sarawak. Parameter-parameter tersebut masing-masing bernilai 52.9 V/m, 46.9 μs, 7.3 μs dan 4.1 μs. Kajian ini menemui variasi dalam ciri-ciri kilat yang merambat di laut dan di darat, dan perkaitannya dengan jarak perambatan. PBP juga telah dikesan sebanyak 52% daripada data kilat yang dikumpul di Sarawak. Secara purata, PBP berdurasi selama 3 ms dan bersela 24 ms dari FRS. Istimewanya, kajian ini telah berjaya merekodkan pengukuran kilat pertama di Malaysia Timur serta menambahkan pengetahuan tentang ciri-ciri kilat di seluruh Malaysia.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AC	-	Alternating Current
AM	-	Arithmetic Mean
BIL	-	Basic Insulation Lightning
BNC	-	Bayonett Neill-Concelman
CA	-	Cloud-to-Air
CC	-	Intercloud
CG	-	Cloud-to-Ground
CPT	-	Chaotic Pulse Trains
ELF	-	Extremely Low Frequency
EMI	-	Electromagnetic Interference
FPS	-	Frames per Second
FRS	-	First Return Stroke
GPS	-	Global Positioning System
IC	-	Intracloud
IEEE	-	Institute of Electrical and Electronics Engineers
LCC	-	Long Continuing Current
LCL	-	Long Continuing Luminosity
LF	-	Low Frequency
LPCR	-	Lower Positive Charge Pocket
LPL	-	Lightning Protection Level
MAX	-	Maximum Frequency
MF	-	Medium Frequency

MIN	-	Minimum Frequency
NBP	-	Narrow Bipolar Pulses
NNBP	-	Narrow Negative Bipolar Pulses
NPBP	-	Narrow Positive Bipolar Pulses
NRS	-	Negative Return Strokes
PB	-	Preliminary Breakdown
PBP	-	Preliminary Breakdown Pulses
PCB	-	Printed Circuit Board
PM	-	Particulates Matter
PRS	-	Positive Return Strokes
PT	-	Pulse Train
RF	-	Radio Frequency
RFI	-	Radio Frequency Interference
RPT	-	Regular Pulse Train
RS	-	Return Strokes
SL	-	Stepped Leader
SNR	-	Signal-to-Noise Ratio
SPD	-	Surge Protection Devices
SRS	-	Subsequent Return Strokes
UAV	-	Unmanned Aerial Vehicle
UTS	-	University of Technology Sarawak
USA	-	United States of America
UTeM	-	Technical University of Malaysia
VHF	-	Very High Frequency

VLF	-	Very Low Frequency
WWLLN	-	World Wide Lightning Location Network.
am	-	Ante meridiem
pm	-	Post meridiem

LIST OF SYMBOLS

TD_{PT}	-	Time Duration of Pulse Train
ST_{PT-SRS}	-	Separation Time between the Pulse Train and Subsequent Return Stroke
TD_{PBP}	-	Time duration of Preliminary Breakdown Pulses
$ST_{PBP-FRS}$	-	Separation time between the Preliminary Breakdown Pulses and First Return Stroke
E_n		Normal Electric Field
V_m		Voltage Measured
T_{ZC}		Zero-Crossing Time
T_{ZP}		Zero-to-Peak Rise Time
$T_{10-90}.$		10 to 90% Rise Time

LIST OF UNITS

m	-	Metre
cm	-	Centimetre
km	-	Kilometre
s	-	Second
ms	-	Millisecond
µs	-	Microsecond
Hz	-	Hertz
kHz	-	Kilohertz
MHz	-	Megahertz
V	-	Volt
mV	-	Millivolt
kA	-	Kiloampere
V/m	-	Volt per metre
kV/m	-	Kilovolt per metre
$(V/m)^2$	-	Volt per metre square
ms^{-1}	-	Metre per second
C	-	Coulomb
Ω	-	Ohm
MΩ	-	Mega ohm
pF	-	Picofarad
MS/s	-	Mega samples per second
%	-	Percent
ms/div	-	Milliseconds per division
^oC	-	Celsius

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Research Background

Lightning is one of the most ancient natural occurrences on Earth and scientists have been studying it since then. The knowledge became more understandable with the help of various sorts of advanced measuring tools and the presence of many experts to conduct numerous in-depth research. However, there are many facts concerning lightning that are still subject to debate. The propagation path of a lightning channel for instance. Paulino et al. [1] and Andreotti et al. [2] agreed that a lightning is assumed to be in a vertical channel. On the other hand, Schoene [3] and Rameli [4] concluded that lightning is typically not a vertical channel. Thus, a high-speed video camera is an excellent advanced measuring tool since it can catch the lightning progression and channels termination point. The integration of advance and existing measuring instruments such as antennas will result in more valuable discoveries on the characteristics of lightning.

Beginning with broad lightning characteristics, researchers delved further into the subject and discovered important parameters involved in lightning formations, such as Preliminary Breakdown (PB), Stepped Leader (SL), Return Strokes (RS), and upward and downward lightning. The correlation between the lightning characteristics and seasonal weathers, topography, and climates were also investigated. As suggested by Xu et al. [5], *"Further research into the relationship between lightning probability and storm characteristics in diverse climatic regimes around the world will be required in the future".* Bourscheidt et al. [6] also proposed a similar idea, *"The lightning activity seems to be affected by terrain, sea breeze, diurnal and nocturnal wind flow".* Given the earth's diversity of geography, climates, and seasons, such study will never be obsolete and will always add value to the lightning knowledge. In addition, there are several micro-scale pulses that have been

found to be associated with lightning electric field signals such as narrow bipolar pulses, preliminary breakdown pulses and chaotic pulse trains. They are also important in understanding lightning events. The importance of investigating CPT was enlightened by Hamzah [7], who stated that "*This research creates paves for various types of analysis on chaotic pulse trains to be conducted in the future in order to better understand lightning activity*". In addition, Gomes et al. [8] also mentioned that, *"One has to continue this study to determine induced voltages, power spectrum and sub-microsecond details of CPT. Such studies will be of great importance to the engineering community dealing on EMI (Electromagnetic Interference) problems".* The advice of these great people frequently inspires and motivates researchers to further their understanding in the future.

Initially, the lightning expertise was established and more advanced in nations within temperate-climate regions before extended to tropical countries. In fact, the 21st century saw a broad range of in-depth and long-term investigations on lightning activities that originated in tropical nations, including positive and negative lightning mechanisms, features, and the correlation between lightning characteristics and topography. All of these researches took place in and around Brazil, Colombia, Sri Lanka, and Malaysia. Despite this advancement, Malaysia is still lagging in lightning research due to a lack of data collection. Hence, Malaysia needs to progressively move forward in lightning research, especially when it comes to determining the features of the electric field involved during a lightning occurrence and their correlation with different climatic circumstances. This will be better done by using an advanced tool, such as a high-speed camera.

1.2 Problem Statement

Malaysia is a tropical country located in Southeast Asia and is so close to the equator, where the number of thunderstorm days is relatively high with countless lightning events reported every year. Unfortunately, the lightning characteristics in Malaysia remain poorly unknown as researches on lightning activity from this region are still lacking. The majority of the available investigations were carried out

utilising a parallel plate antenna and an oscilloscope to collect the lightning electric field data. However, this measurement setup only captures and analyses the waveform of the electric field generated from the lightning. If one is to investigate and understand the lightning progression and channel behaviour, the method to measure the electric field needs to be further enhanced. Therefore, a high-speed video camera is an ideal additional instrument to improve the measuring technique as the device can be used to capture the lightning events, as desired. This is crucial since the behaviour of the lightning channel is still debatable. It is also worth noting that there is no report available on lightning observation using a high-speed camera in Malaysia up to 2017.

Secondly, the mechanism that initiates the formation of lightning inside thunderclouds has yet to be understood. It is known that FRS always starts with tiny little unipolar and bipolar pulses, known as PBP, that can be correlated to the initial stage of lightning formation. Meanwhile, PT is commonly found to precede the Subsequent Return Strokes (SRS) that it may be considered as the initiation pulse of the SRS occurrences. In addition to FRS, SRS occurrences are also important in understanding the lightning formation that PT deserves an in-depth study. However, there are only a few available data that was successfully collected in Malaysia resulting in a paucity of research on PT characteristics.

Furthermore, all previous lightning studies in Malaysia were based on data collected and recorded from West Malaysia only. To date, no lightning data has ever been recorded and reported from East Malaysia in any lightning research work in Malaysia. Geographically separated, West Malaysia is a peninsula projected from the Asian Continent, while East Malaysia is part of Borneo Island. Thus, it is reasonable to conduct an exploratory study including both West and East Malaysia so that a conclusive lightning study, which covers data from all regions of Malaysia, can be established. It is also crucial to examine the relationship between lightning formation and lightning characteristics with various elements, such as climate, temperature, and propagation medium, to name a few. Therefore, a profound investigation on the data must be done throughout Malaysia to be advanced on a par with temperate countries in lightning research.

1.3 Research Objectives

This exploratory study seeks to uncover a better understanding of lightning characteristics observed in Malaysia using both the parallel plate antenna and high-speed camera. The data obtained would be used:

1. To optically investigate the cloud-to-ground lightning characteristics from high-speed images observed in West Malaysia.
2. To characterise the Pulse Train (PT) in cloud-to-ground lightning in West Malaysia in the time and frequency domain.
3. To analyse the temporal characteristics of the cloud-to-ground lightning electric field for the data obtained from East Malaysia.

1.4 Research Hypothesis

Lightning channels can be categorised into two types, namely vertical and tortuous. The tortuous lightning is considered the common pattern of lightning conducting channels, as agreed in past studies [9, 10]. The approach employed in this field campaign will be extremely useful and significant in investigating lightning mechanisms, as reported by Ballarotti et al. [11] and Tran et al. [12]. In addition, various categories of PT and their radiation features generated by lightning in Malaysia would be discovered. Using the wavelet analysis, the PT features, especially its radiation power and frequency spectrum, could also be determined. Moreover, recent literature showed that the parameters of the lightning electric field vary depending on the propagation medium, which involves distinct geological environments [13, 14]. Therefore, the lightning striking over South China Sea near Sarawak may have different characteristics than those striking on the Sarawak land.

1.5 Research Scope

This study focuses on lightning characterization using statistical analysis or numerical inference. Characterization seeks to find and comprehend potential causes of variance, whereas statistical analysis assists in identifying trends and patterns in data. Several scopes are defined to guarantee that the investigation is carried out within the established boundaries. A high-speed camera (Chronos 1.4) with a frame rate of 2873 Frames per Second (FPS) was used to examine the progression of CG lightning in Malacca. The observation station was installed in the Technology Campus, Technical University of Malaysia (UTeM). The field measurements were carried out from April 2018 until December 2019. Temporal analysis was done solely based on the recorded videos by using a video editor software (Wondershare Filmora X). The data used to optically investigate the lightning channel behaviour, including:

(a) The number of tortuous and vertical channels.
(b) The number of single and multiple strokes lightning.
(c) The number of lightning that created new channels.
(d) Identify the stroke interval and First Return Stroke (FRS) interval.

Besides that, CG lightning electric field waveforms with pulse trains were also collected in Malacca using a parallel plate antenna and fast field circuit in April 2019. These data were used to investigate the significant profiles based on the time- and frequency-domain of PT using the wavelet analysis in MATLAB. The pulse trains were characterised by the following characteristics:

(a) The type of categories of PT that exist.
(b) The percentage of PT found in a single stroke.
(c) The percentage of PT being an initiation event to Subsequent Return Strokes (SRS).
(d) The PT features by stroke orders, including the PT duration and PT to SRS separation time.

(e) The power spectrum produced by PT using the wavelet analysis in MATLAB.

A similar antenna and fast field circuit were also installed in the lightning measurement station located in the campus compound of University of Technology Sarawak (UTS) in Sibu, Sarawak. Since the data in Sibu, Sarawak was collected during the beginning of Malaysian Movement Control Order due to COVID-19 pandemic, the measurement of CG lightning electric field can only be performed in March and July 2020 only. The period of this measurement had considered the active occurrence of lightning activities which usually occur during the monsoon season from March to July. By adopting the atmospheric sign convention, the electric field obtained in Sarawak were analysed to discover the following characteristics:

(a) The normal electric field (E_n), zero-crossing time (T_{ZC}), zero-to-peak rise time (T_{ZP}), and 10–90% rise time (T_{10-90}) for the RS variation in different propagation medium; sea and land
(b) The percentage of detectable PBP, PT duration, and the separation time between PBP and FRS

1.6 Contributions of Research

All the findings in this research work lead to uncovering new knowledge on lightning physics, specifically in Malaysia, and generally in tropical regions. The contributions of this thesis are outlined as below:

I. CG Lightning Observation using a High-Speed Camera

Lightning photography is the most recent approach in lightning research, which had not yet been implemented or published in Malaysia prior to this study. In other words, this study is the first of its kind in Malaysia which is one of the novel outcomes of this study. The progression of CG lightning was visually examined

using a high-speed camera. This technology was used to record the behaviour of lightning channels, including vertical and tortuous channel characteristics. All these findings contribute to an added value in the knowledge of lightning physics. Based on the findings, tortuous was considered the typical type of lightning channel that occurs in Malaysia. Other than that, to the best of the author's knowledge, several types of lightning events, such as fork lightning, LCL, and upward initiated lightning, were significantly the first optical observation using high-speed camera reported in Malaysia. The tendency of lightning to create a new channel is an important aspect that needs to be taken into consideration to further understand the fatal behaviour of lightning.

II. PT Characteristics in Time and Frequency Domains

The implementation of both temporal and frequency analysis allows us to develop more lightning characteristics. Based on the CG lightning electric field waveform, two new PT categories have been identified and added to the current list of the existing PT types. There was a 99.8% chance of initiating SRS if PT was present. The PT time duration and the separation time between the PT and SRS were obtained from the temporal analysis. Meanwhile, the wavelet analysis in MATLAB produced information on the peak power, spectrum, and spread region frequency of the PT. The results have remarkably contributed to the enhancement of lightning physic knowledge, which could also be applicable for the development of lightning warning and monitoring systems. In addition, the findings of this study would also facilitate the development of effective lightning sensors. Since all the PT signals in this study were found to precede SRS, thus, the sensors were able to detect the PT signal based on the spectral frequency value and anticipate lightning multiplication. The anticipation of the lightning multiplication allows us to estimate the amount of harmful energy generated from the event. This information is important in designing protective devices, such as surge arresters [15]. The wavelet analysis of the PT samples is also beneficial in lightning research as it significantly contributes to the design of lightning protection systems. For instance, the PT peak power and the spectral and spread region are potentially useful in designing lightning Radio Frequency Interference (RFI) filters for electronic equipment and communication

systems. Most systems operating in the VLF, LF, and MF range are prone to interference. Therefore, the RFI filter is designed to block the undesired RF energy while also allowing RF energy to flow through to the ground [16]. Furthermore, each lightning discharge emits electromagnetic waves that propagate away from the lightning channel and are directed over the earth through the Earth-ionosphere waveguide. While the frequency of the radiation determines the attenuation of these waves, the highest frequencies are the first to be suppressed, whereas the lowest frequencies can travel long distances. Therefore, a distant thunderstorm is very feasible to be detected using ground sensor networks that detect the emitted waves [17]. The thunderstorm can be monitored continuously even in remote regions with sensors that are highly sensitive to Extremely Low Frequency (ELF) band waveforms. This indicates that lightning sensors development is very crucial in lightning monitoring systems, which opens the opportunity to study lightning characteristics and activities.

III. Temporal Analysis on CG Lightning Characteristics Obtained from East Malaysia

A lightning measurement station was developed in Sarawak, Malaysia, which was the first lightning data acquisition in the region. Four lightning parameters, namely the normal electric field, the zero-crossing time, the zero-to-peak rise time, and the 10–90% rise time of the RS, were all recorded. On top of enriching the lightning physics knowledge, the findings in this chapter can be implemented in several applications. It was stated that a higher voltage above the BIL level poses a higher possibility for equipment damages due to the induced voltage [18]. Thus, the value of E_n can be very useful in improving the selection of insulating materials for lightning protection. This can be applied in the Standard BIL used by the Sarawak Energy listed in the Sarawak Energy List of Material, 2017 [19]. As aforementioned, the T_{ZC} value corresponds to the quantity of charge ttransferred through the voltage in a certain time interval. Therefore, it is very useful in designing surge arresters to determine the energy absorption capability of the instrument [20]. This would minimise the risk of surge arrester failure rate. Meanwhile, both T_{ZP} and T_{10-90} can be used to classify SPDs, as outlined in the Malaysian Standard of Low-Voltage

Surge Protective Devices (MS IEC 61643) [21]. SPD Type 1 is characterised by a longer rise time than SPD Type 2. All four lightning parameters (E_n, T_{ZC}, T_{ZP} and T_{10-90}) can also be used to improve the reliability of the LPL determination outlined in Malaysian Standard of Protection Against Lightning (MS IEC 62305) [22]. Besides the RS lightning parameter, this study conducted a thorough analysis of the PBP_{TD}. In terms of its application, PBP occurrences and features are important to be considered in developing prediction algorithms for lightning monitoring systems. The presence of PBP train in the lightning waveform provides a 52% of probability in the train's ability to initiate FRS. Because FRS is known to be connected with high voltages, lightning monitoring systems may be the first to respond in safeguarding structures and electronic equipment from the risks of lightning overvoltage.

1.7 Thesis Outline

In this thesis, Chapter 1 covered the surface idea of the research study. Chapter 2 presented the lightning literature, stretching from the electricity discovery by Benjamin Franklin until the most recent reports on lightning research. The chapter discussed the evolution of lightning research, including the measurement tools and the lightning parameters of interest. In Chapter 3, the hardware installation and analysis methods are thoroughly described. This is including the high-speed image observation, wavelet analysis and the lightning characteristics measurement. Meanwhile, the findings of the practical measurements conducted in three separate periods from 2018 to 2020 were presented in Chapter 4. Several significant characteristics of four lightning pulses are investigated in this research, including PBP, PT, FRS, and SRS. Finally, Chapter 5 highlighted the study's findings as the conclusions of this study. This chapter also included recommendations for potential future works. In addition, the Gantt chart, as shown in Appendix A, was designed based on the methodology to achieve the research objectives. This study was projected for completion within four and half years of experimental and analysis works.

REFERENCES

[1] J. O. S. Paulino, C. F. Barbosa, I. J. Lopes, and W. do Couto Boaventura, "An approximate formula for the peak value of lightning-induced voltages in overhead lines," *IEEE Transactions on Power Delivery*, vol. 25, no. 2, pp. 843-851, 2009.

[2] A. Andreotti, A. Pierno, and V. A. Rakov, "An analytical approach to calculation of lightning induced voltages on overhead lines in case of lossy ground—Part I: Model development," *IEEE transactions on power delivery*, vol. 28, no. 2, pp. 1213-1223, 2013.

[3] J. Schoene, "Analysis of parameters of rocket-triggered lightning measured during the 1999 and 2000 camp blanding experiment and modeling of electric and magnetic field derivatives using the transmission line model," University of Florida, 2002.

[4] N. Rameli, "Lightning-Induced Voltage on Distribution Line Due to Inclined Lightning Channel," Universiti Putra Malaysia, 2013.

[5] W. Xu, E. J. Zipser, C. Liu, and H. Jiang, "On the relationships between lightning frequency and thundercloud parameters of regional precipitation systems," *Journal of Geophysical Research: Atmospheres*, vol. 115, no. D12, 2010.

[6] V. Bourscheidt, O. Pinto Jr, and K. P. Naccarato, "The effects of Sao Paulo urban heat island on lightning activity: Decadal analysis (1999–2009)," *Journal of Geophysical Research: Atmospheres*, vol. 121, no. 9, pp. 4429-4442, 2016.

[7] M. N. Hamzah, "Distinct Characteristics Of Cloud-To-Ground Lightning Electric Fields Generated in malaysia," *Universiti Putra Malaysia*, 2015.

[8] C. Gomes, V. Cooray, M. Fernando, R. Montano, and U. Sonnadara, "Characteristics of chaotic pulse trains generated by lightning flashes," *Journal of Atmospheric and Solar-Terrestrial Physics*, vol. 66, no. 18, pp. 1733-1743, 2004.

[9] T.-X. Song, Y.-H. Liu, and J.-M. Xiong, "Computations of electromagnetic fields radiated from complex lightning channels," *Progress In Electromagnetics Research*, vol. 73, pp. 93-105, 2007.

[10] V. P. Idone and R. E. Orville, "Channel tortuosity variation in Florida triggered lightning," *Geophysical research letters*, vol. 15, no. 7, pp. 645-648, 1988.

[11] M. Ballarotti, M. Saba, and O. Pinto Jr, "High-speed camera observations of negative ground flashes on a millisecond-scale," *Geophysical Research Letters*, vol. 32, no. 23, 2005.

[12] M. Tran and V. Rakov, "Initiation and propagation of cloud-to-ground lightning observed with a high-speed video camera," *Scientific reports*, vol. 6, p. 39521, 2016.

[13] Y. Zhang, J. Gu, and E. Zhang, "Analysis of underground propagation effects of lightning electromagnetic fields in different geological environments," *International Journal of Applied Electromagnetics and Mechanics*, vol. 62, no. 4, pp. 861-873, 2020.

[14] Z. Abdul-Malek, A. M. Yusof, C.-L. Wooi, and M. A. B. Sidik, "Lightning-Generated Electric Field Over Land and Sea at Northern Peninsular Malaysia," *Available at SSRN 4051358*.

[15] V. Rakov, "Lightning parameters for engineering applications (keynote speech)," in *Electromagnetic Compatibility (APEMC), 2010 Asia-Pacific Symposium on*, 2010: IEEE, pp. 1120-1123.

[16] A. GLobal, "Radio Frequency Interference Filter (RFI-P)," *Copper Apparatus*, 2020.

[17] C. Price, "Lightning sensors for observing, tracking and nowcasting severe weather," *Sensors*, vol. 8, no. 1, pp. 157-170, 2008.

[18] M. Izadi, M. S. Abd Rahman, M. Z. A. Ab-Kadir, C. Gomes, J. Jasni, and M. Hajikhani, "The influence of lightning induced voltage on the distribution power line polymer insulators," *PloS one*, vol. 12, no. 2, p. e0172118, 2017.

[19] S. E. Berhad, "List of Materials," *Acceptable for Use on Systems of Sarawak Energy Berhad*, 2017.

[20] S. Milan, "Selection of the surge arrester energy absorption capability relating to lightning overvoltages," in *CIRED 2005-18th International Conference and Exhibition on Electricity Distribution*, 2005: IET, pp. 1-3.

[21] D. o. S. Malaysia, "MS IEC 61643-12:2012," *Low-voltage surge protective devices - Part 12: Surge protective devices connected to low-voltage power distribution systems - Selection and application principles (First revision) (IEC 61643-12:2008, IDT),* 2018.

[22] D. o. S. Malaysia, "MS IEC 62305-1:2007," *Protection Against LIGHTNING - Part 1: General Principles (First Revision) (IEC 62305-1:2006, IDT),* 2018.

[23] T. Editors, "Lightning Meteorology," *Encyclopaedia Britannica,* 2018.

[24] Y. Kim, J. Jo, D. Kim, H. Lee, and R. Myong, "Effects of lightning on UAM aircraft: Complex zoning and direct effects on composite prop-rotor blade," *Aerospace Science and Technology,* vol. 124, p. 107560, 2022.

[25] B. Franklin, *Experiments And Observations On Electricity: Made At Philadelphia in America, by Benjamin Franklin, LLD and FRS To which are Added, Letters and Papers On Philosophical Subjects*. David Henry, 1769.

[26] G. Berger, "Jacques de Romas and his experiments on the electric nature of lightning," in *Lightning (APL), 2011 7th Asia-Pacific International Conference on*, 2011: IEEE, pp. 1-7.

[27] H. Norinder, "Experimental lightning research," *Journal of the Franklin Institute,* vol. 253, no. 5, pp. 471-504, 1952.

[28] W. Humphreys, "Note on the Crushing of a Copper Tube by Lightning," *Monthly Weather Review,* vol. 43, no. 8, pp. 396-398, 1915.

[29] F. Kohlrausch, "On the thermal conductivity of hard and soft steel," *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science,* vol. 25, no. 156, pp. 448-450, 1888.

[30] H. Norinder, "Electric thunderstorm field researches," *Electrical World,* vol. 83, no. 5, p. 223, 1924.

[31] K. Berger, "Novel observations on lightning discharges: Results of research on Mount San Salvatore," *Journal of the Franklin Institute,* vol. 283, no. 6, pp. 478-525, 1967.

[32] C. E. R. Bruce and R. H. Golde, "The lightning discharge," *Journal of the Institution of Electrical Engineers-Part II: Power Engineering,* vol. 88, no. 6, pp. 487-505, 1941.

[33] P. L. Rustan, M. A. Uman, D. G. Childers, W. H. Beasley, and C. L. Lennon, "Lightning source locations from VHF radiation data for a flash at Kennedy

Space Center," *Journal of Geophysical Research: Oceans,* vol. 85, no. C9, pp. 4893-4903, 1980.

[34] W. Beasley, M. A. Uman, and P. Rustan Jr, "Electric fields preceding cloud-to-ground lightning flashes," *Journal of Geophysical Research: Oceans,* vol. 87, no. C7, pp. 4883-4902, 1982.

[35] C. Baum, E. Breen, J. Oneill, C. Moore, and D. Hall, "Measurement of electromagnetic properties of lightning with 10 nanosecond resolution," 1980.

[36] R. Fisher, G. Schnetzer, R. Thottappillil, V. Rakov, M. Uman, and J. Goldberg, "Parameters of triggered-lightning flashes in Florida and Alabama," *Journal of Geophysical Research: Atmospheres,* vol. 98, no. D12, pp. 22887-22902, 1993.

[37] A. Hussein, W. Janischewskyj, M. Milewski, V. Shostak, W. Chisholm, and J. Chang, "Current waveform parameters of CN Tower lightning return strokes," *Journal of electrostatics,* vol. 60, no. 2-4, pp. 149-162, 2004.

[38] T. A. Warner, K. L. Cummins, and R. E. Orville, "Upward lightning observations from towers in Rapid City, South Dakota and comparison with National Lightning Detection Network data, 2004–2010," *Journal of Geophysical Research: Atmospheres,* vol. 117, no. D19, 2012.

[39] A. Nag, B. A. DeCarlo, and V. A. Rakov, "Analysis of microsecond-and submicrosecond-scale electric field pulses produced by cloud and ground lightning discharges," *Atmospheric Research,* vol. 91, no. 2-4, pp. 316-325, 2009.

[40] D. Petersen and W. Beasley, "High-speed video observations of the preliminary breakdown phase of a negative cloud-to-ground lightning flash," in *XV International Conference on Atmospheric Electricity, Norman, Okla*, 2014, pp. 15-20.

[41] X. Kong, X. Qie, and Y. Zhao, "Characteristics of downward leader in a positive cloud-to-ground lightning flash observed by high-speed video camera and electric field changes," *Geophysical Research Letters,* vol. 35, no. 5, 2008.

[42] F. H. Heidler, M. Manhardt, and K. Stimper, "Characteristics of upward positive lightning initiated from the Peissenberg Tower, Germany," *IEEE Transactions on Electromagnetic Compatibility*, vol. 57, no. 1, pp. 102-111, 2015.

[43] D. Randerson and J. B. Sanders, "Characterization of cloud-to-ground lightning flashes on the Nevada Test Site," 2002.

[44] B. J. Vogt and S. J. Hodanish, "A geographical analysis of warm season lightning/landscape interactions across Colorado, USA," *Applied Geography,* vol. 75, pp. 93-103, 2016.

[45] E. Williams, "Lightning and climate: A review," *Atmospheric Research,* vol. 76, no. 1-4, pp. 272-287, 2005.

[46] S. A. Fleenor, C. J. Biagi, K. L. Cummins, E. P. Krider, and X.-M. Shao, "Characteristics of cloud-to-ground lightning in warm-season thunderstorms in the Central Great Plains," *Atmospheric Research,* vol. 91, no. 2-4, pp. 333-352, 2009.

[47] R. E. Orville, G. R. Huffines, W. R. Burrows, R. L. Holle, and K. L. Cummins, "The North American lightning detection network (NALDN)—First results: 1998–2000," *Monthly Weather Review,* vol. 130, no. 8, pp. 2098-2109, 2002.

[48] L. R. Soriano, F. De Pablo, and C. Tomas, "Ten-year study of cloud-to-ground lightning activity in the Iberian Peninsula," *Journal of Atmospheric and Solar-Terrestrial Physics,* vol. 67, no. 16, pp. 1632-1639, 2005.

[49] F. Perry, "The measurement of lightning voltages and currents in South Africa and Nigeria—1935 to 1937," *Journal of the Institution of Electrical Engineers-Part II: Power Engineering,* vol. 88, no. 2, pp. 69-87, 1941.

[50] F. Perry, G. Webster, and P. Baguley, "The measurement of lightning voltages and currents in Nigeria. Part 2: 1938–1939," *Journal of the Institution of Electrical Engineers-Part II: Power Engineering,* vol. 89, no. 9, pp. 185-203, 1942.

[51] B. Schonland and H. Collens, "Progressive lightning," *Proc. R. Soc. Lond. A,* vol. 143, no. 850, pp. 654-674, 1934.

[52] B. Schonland, D. Malan, and H. Collens, "Progressive lightning—II," *Proc. R. Soc. Lond. A,* vol. 152, no. 877, pp. 595-625, 1935.

[53] N. Clarence and D. Malan, "Preliminary discharge processes in lightning flashes to ground," *Quarterly Journal of the Royal Meteorological Society,* vol. 83, no. 356, pp. 161-172, 1957.

[54] D. Malan, "The electrical processes in the intervals between the strokes of a ligthning discharge," *preceedings of the royal society Mathematcal, Physical & Engineering Science,* vol. 206, no. 10 April 1951, 1950.

[55] N. Kitagawa and M. Brook, "A comparison of intracloud and cloud-to-ground lightning discharges," *Journal of Geophysical Research,* vol. 65, no. 4, pp. 1189-1201, 1960.

[56] D. Harris and Y. Salman, "The measurement of lightning characteristics in northern Nigeria," *Journal of Atmospheric and Terrestrial Physics,* vol. 34, no. 5, pp. 775-786, 1972.

[57] V. Cooray and S. Lundquist, "Characteristics of the radiation fields from lightning in Sri Lanka in the tropics," *Journal of Geophysical Research: Atmospheres,* vol. 90, no. D4, pp. 6099-6109, 1985.

[58] V. Cooray and S. Lundquist, "On the characteristics of some radiation fields from lightning and their possible origin in positive ground flashes," *Journal of Geophysical Research: Oceans,* vol. 87, no. C13, pp. 11203-11214, 1982.

[59] E. P. Krider, C. D. Weidman, and R. C. Noggle, "The electric fields produced by lightning stepped leaders," *Journal of Geophysical Research,* vol. 82, no. 6, pp. 951-960, 1977.

[60] V. Cooray and H. Pérez, "Some features of lightning flashes observed in Sweden," *Journal of Geophysical Research: Atmospheres,* vol. 99, no. D5, pp. 10683-10688, 1994.

[61] Z. A. Baharudin, N. A. Ahmad, M. Fernando, V. Cooray, and J. Mäkelä, "Comparative study on preliminary breakdown pulse trains observed in Johor, Malaysia and Florida, USA," *Atmospheric research,* vol. 117, pp. 111-121, 2012.

[62] A. Hazmi, R. Desmiarti, P. Emeraldi, M. I. Hamid, and N. Takagi, "Observed Electric Field Changes of Positive Lightning Flashes Preceded by Preliminary Breakdown in Padang," *International Journal on Electrical Engineering and Informatics,* vol. 9, no. 2, p. 284, 2017.

[63] S. Visacro, M. Guimaraes, and M. H. Murta Vale, "Features of Upward Positive Leaders Initiated From Towers in Natural Cloud-to-Ground Lightning Based on Simultaneous High-Speed Videos, Measured Currents, and Electric Fields," *Journal of Geophysical Research: Atmospheres,* vol. 122, no. 23, 2017.

[64] S. Pawar, D. Lal, and P. Murugavel, "Lightning characteristics over central India during Indian summer monsoon," *Atmospheric research,* vol. 106, pp. 44-49, 2012.

[65] P. R. Kumar and A. Kamra, "Land–sea contrast in lightning activity over the sea and peninsular regions of South/Southeast Asia," *Atmospheric research,* vol. 118, pp. 52-67, 2012.

[66] D. Aranguren, J. López, J. Inampués, H. Torres, and H. Betz, "Cloud-to-ground lightning activity in Colombia and the influence of topography," *Journal of Atmospheric and Solar-Terrestrial Physics,* vol. 154, pp. 182-189, 2017.

[67] C.-L. Wooi, Z. Abdul-Malek, B. Salimi, N. A. Ahmad, K. Mehranzamir, and S. Vahabi-Mashak, "A comparative study on the positive lightning return stroke electric fields in different meteorological conditions," *Advances in Meteorology,* vol. 2015, 2015.

[68] N. Mayet, J. Knight, and S. W. Grab, "Spatial and temporal patterns of lightning strikes in the eastern Lesotho Highlands, southern Africa," *South African Geographical Journal,* vol. 98, no. 2, pp. 321-336, 2016.

[69] J. Herrera, C. Younes, and L. Porras, "Cloud-to-ground lightning activity in Colombia: A 14-year study using lightning location system data," *Atmospheric Research,* 2017.

[70] C. Wong, "The Investigation of Ground and Intra-cloud Lightning Discharges in Malaysia," Fakulti Kejuruteraan, Universiti Malaya, 1974.

[71] C. Wong and K. Lim, "The inclination of intracloud lightning discharges," *Journal of Geophysical Research: Oceans,* vol. 83, no. C4, pp. 1905-1912, 1978.

[72] H. Norinder and O. Dahle, *Measurements by frame aerials of current variations in lightning discharges*. Almqvist & Wiksells, 1945.

[73] S. C. Lee, K. Lim, M. Meiappa, and A. Liew, "Determination of lightning current using frame aerials," *IEEE Transactions on Power Apparatus and Systems,* no. 5, pp. 1669-1675, 1979.

[74] P. N. S. A. Rahman and Z. A. Baharudin, "Investigation of Non-Identical Polarity of Lightning Preliminary Breakdown Pulse Train to that of Negative First Return Pulse in Malaysia," *International Journal of Simulation--Systems, Science & Technology,* vol. 17, no. 41, 2016.

[75] N. Shaari, "Narrow band field measurement generated by lightning flashes," Universiti Teknikal Malaysia Melaka, 2013.

[76] N. A. Ahmad, M. Fernando, Z. A. Baharudin, V. Cooray, H. Ahmad, and Z. A. Malek, "Characteristics of narrow bipolar pulses observed in Malaysia," *Journal of Atmospheric and Solar-Terrestrial Physics,* vol. 72, no. 5-6, pp. 534-540, 2010.

[77] Z. A. Baharudin, N. A. Ahmad, J. Mäkelä, M. Fernando, and V. Cooray, "Negative cloud-to-ground lightning flashes in Malaysia," *Journal of Atmospheric and Solar-Terrestrial Physics,* vol. 108, pp. 61-67, 2014.

[78] Z. A. Baharudin, V. Cooray, M. Rahman, P. Hettiarachchi, and N. A. Ahmad, "Electric field changes generated by preliminary breakdown pulse for positive lightning ground flashes in Sweden," 2014.

[79] Z. A. Baharudin, M. Fernando, N. A. Ahmad, J. Mäkelä, M. Rahman, and V. Cooray, "Electric field changes generated by the preliminary breakdown for the negative cloud-to-ground lightning flashes in Malaysia and Sweden," *Journal of Atmospheric and Solar-Terrestrial Physics,* vol. 84, pp. 15-24, 2012.

[80] C. L. Wooi, Z. Abdul-Malek, N. A. Ahmad, M. Mokhatri, and A. H. Khavari, "A Review of Recent Studies on Positive Lightning," in *Applied Mechanics and Materials*, 2016, vol. 818: Trans Tech Publ, pp. 134-139.

[81] C. L. Wooi, Z. Abdul-Malek, N. A. Ahmad, M. Mokhtari, and A. H. Khavari, "Cloud-to-Ground Lightning in Malaysia: A Review Study," in *Applied Mechanics and Materials*, 2016, vol. 818: Trans Tech Publ, pp. 140-145.

[82] B. Salimi, K. Mehranzamir, and Z. Abdul-Malek, "Statistical analysis of lightning electric field measured under Malaysian condition," *Asia-Pacific Journal of Atmospheric Sciences,* vol. 50, no. 2, pp. 133-137, 2014.

[83] C. Foust, "instruments for Lightning Measurements," *General Electric Review,* vol. 34, p. 235, 1931.

[84] H. Halperin, J. Clem, and K. Miller, "Transient voltages on bonded cable sheaths," *Electrical Engineering,* vol. 54, no. 1, pp. 73-82, 1935.

[85] C. Wagner and G. McCann, "New instruments for recording lightning currents," *Electrical Engineering,* vol. 59, no. 12, pp. 1061-1068, 1940.

[86] H. Norinder, "The cathode oscillograph as used in the study of lightning and other surges on transmission lines," *Transactions of the American Institute of Electrical Engineers,* vol. 47, no. 2, pp. 446-455, 1928.

[87] H. Kuehni and S. Ramo, "A new high-speed cathode-ray oscillograph," *Electrical Engineering,* vol. 56, no. 6, pp. 721-728, 1937.

[88] W. Lewis and C. Foust, "Lightning investigation on transmission lines," *Transactions of the American Institute of Electrical Engineers,* vol. 49, no. 3, pp. 917-928, 1930.

[89] F. Horner, "The design and use of instruments for counting local lightning flashes," *Proceedings of the IEE-Part B: Electronic and Communication Engineering,* vol. 107, no. 34, pp. 321-330, 1960.

[90] R. Golde, "The frequency of occurrence and the distribution of lightning flashes to transmission lines," *Electrical Engineering,* vol. 64, no. 12, pp. 902-910, 1945.

[91] E. Bell, "Lightning Investigation on a 220-Kv System--II," *Transactions of the American Institute of Electrical Engineers,* vol. 55, no. 12, pp. 1306-1313, 1936.

[92] W. Lewis and C. Foust, "Lightning Investigation on Transmission Lines---II," *Transactions of the American Institute of Electrical Engineers,* vol. 50, no. 3, pp. 1139-1146, 1931.

[93] E. Bell and A. Price, "Lightning Investigation on the 220-Kv. System of the Pennsylvania Power & Light Company (1930)," *Transactions of the American Institute of Electrical Engineers,* vol. 50, no. 3, pp. 1101-1110, 1931.

[94] K. Berger and E. Vogelsanger, "New results of lightning observations," *Planetary Electrodynamics,* vol. 1, pp. 489-510, 1969.

[95] P. B. Adhikari, S. Sharma, K. Baral, and V. A. Rakov, "Unusual lightning electric field waveforms observed in Kathmandu, Nepal, and Uppsala, Sweden," *Journal of Atmospheric and Solar-Terrestrial Physics,* vol. 164, pp. 172-184, 2017.

[96] X. Qie, Z. Wang, D. Wang, and M. Liu, "Characteristics of positive cloud-to-ground lightning in Da Hinggan Ling forest region at relatively high latitude, northeastern China," *Journal of Geophysical Research: Atmospheres,* vol. 118, no. 24, 2013.

[97] M. Tran and V. Rakov, "Initiation and propagation of cloud-to-ground lightning observed with a high-speed video camera," *Scientific reports*, vol. 6, 2016.

[98] S. Visacro, M. Guimaraes, and M. H. M. Vale, "Features of upward positive leaders initiated from towers in natural cloud-to-ground lightning based on simultaneous high-speed videos, measured currents and electric fields," *Journal of Geophysical Research: Atmospheres*, 2017.

[99] B. Turman, "Analysis of lightning data from the DMSP satellite," *Journal of Geophysical Research: Oceans*, vol. 83, no. C10, pp. 5019-5024, 1978.

[100] H. J. Christian and J. Latham, "Satellite measurements of global lightning," *Quarterly Journal of the Royal Meteorological Society*, vol. 124, no. 549, pp. 1771-1773, 1998.

[101] R. M. Reap, "Evaluation of cloud-to-ground lightning data from the western United States for the 1983–84 summer seasons," *Journal of Climate and Applied Meteorology*, vol. 25, no. 6, pp. 785-799, 1986.

[102] D. R. Poelman, W. Schulz, and C. Vergeiner, "Performance characteristics of distinct lightning detection networks covering Belgium," *Journal of Atmospheric and Oceanic Technology*, vol. 30, no. 5, pp. 942-951, 2013.

[103] H. Norinder, E. Knudsen, and B. Vollmer, "Multiple strokes in lightning channels," *Recent Advances in Atmospheric Electricity LG Smith*, vol. 525, 1958.

[104] A. Nickolaenko and L. Rabinowicz, "Study of the annual changes of global lightning distribution and frequency variations of the first Schumann resonance mode," *Journal of Atmospheric and Terrestrial Physics*, vol. 57, no. 11, pp. 1345-1348, 1995.

[105] H. Kikuchi *et al.*, "Simultaneous observations of optical lightning from space and LF band lightning waveforms from the ground," *Geophysical Research Letters*, vol. 44, no. 2, pp. 1123-1131, 2017.

[106] A. R. Jacobson, K. L. Cummins, M. Carter, P. Klingner, D. Roussel-Dupré, and S. O. Knox, "FORTE radio-frequency observations of lightning strokes detected by the National Lightning Detection Network," *Journal of Geophysical Research: Atmospheres*, vol. 105, no. D12, pp. 15653-15662, 2000.

[107] B. Turman and B. Edgar, "Global lightning distributions at dawn and dusk," *Journal of Geophysical Research: Oceans,* vol. 87, no. C2, pp. 1191-1206, 1982.

[108] H. J. Christian *et al.*, "Global frequency and distribution of lightning as observed from space by the Optical Transient Detector," *Journal of Geophysical Research: Atmospheres,* vol. 108, no. D1, 2003.

[109] T. P. Lericos, H. E. Fuelberg, A. I. Watson, and R. L. Holle, "Warm season lightning distributions over the Florida peninsula as related to synoptic patterns," *Weather and Forecasting,* vol. 17, no. 1, pp. 83-98, 2002.

[110] D. J. Boccippio, K. L. Cummins, H. J. Christian, and S. J. Goodman, "Combined satellite-and surface-based estimation of the intracloud–cloud-to-ground lightning ratio over the continental United States," *Monthly Weather Review,* vol. 129, no. 1, pp. 108-122, 2001.

[111] E. Williams and S. Stanfill, "The physical origin of the land–ocean contrast in lightning activity," *Comptes Rendus Physique,* vol. 3, no. 10, pp. 1277-1292, 2002.

[112] A. B. Chen *et al.*, "Global distributions and occurrence rates of transient luminous events," *Journal of Geophysical Research: Space Physics,* vol. 113, no. A8, 2008.

[113] R. Thottappillil, M. A. Uman, and G. Diendorfer, "Influence of channel base current and varying return stroke speed on the calculated fields of three important return stroke models," 1991.

[114] M. Zhou *et al.*, "On the variation of optical return stroke speed along the bottom of lightning channel," *IEEE Transactions on Electromagnetic Compatibility,* vol. 61, no. 3, pp. 766-777, 2019.

[115] Y. Zhang, J. Gu, and E. Zhang, "Analysis of underground propagation effects of lightning electromagnetic fields in different geological environments," *International Journal of Applied Electromagnetics and Mechanics,* no. Preprint, pp. 1-13, 2020.

[116] F. H. Heidler and C. Paul, "Field Enhancement by Lightning Strikes to Tall Tower Versus Lightning Strikes to Flat Ground," *IEEE Transactions on Electromagnetic Compatibility*, 2020.

[117] M. Tran and V. Rakov, "Attachment process in subsequent strokes and residual channel luminosity between strokes of natural lightning," *Journal of*

Geophysical Research: Atmospheres, vol. 120, no. 23, pp. 12,248-12,258, 2015.

[118] A. Shoory, F. Rachidi, M. Rubinstein, R. Moini, and S. H. H. Sadeghi, "Analytical expressions for zero-crossing times in lightning return-stroke engineering models," *IEEE transactions on electromagnetic compatibility,* vol. 51, no. 4, pp. 963-974, 2009.

[119] A. Andreotti, U. De Martinis, C. Petrarca, V. A. Rakov, and L. Verolino, "Lightning electromagnetic fields and induced voltages: Influence of channel tortuosity," in *2011 XXXth URSI General Assembly and Scientific Symposium*, 2011: IEEE, pp. 1-4.

[120] A. Andreotti, C. Petrarca, and A. Pierno, "On the effects of channel tortuosity in lightning-induced voltages assessment," *IEEE Transactions on Electromagnetic Compatibility*, vol. 57, no. 5, pp. 1096-1102, 2015.

[121] H. Hoffert, "XV. Intermittent lightning-flashes," *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, vol. 28, no. 171, pp. 106-109, 1889.

[122] V. A. Rakov and M. A. Uman, *Lightning: physics and effects*. Cambridge University Press, 2003.

[123] W. D. Rust, D. R. MacGorman, and R. T. Arnold, "Positive cloud-to-ground lightning flashes in severe storms," *Geophysical Research Letters,* vol. 8, no. 7, pp. 791-794, 1981.

[124] Atmo, "Lecture 15: Lightning Part 2," *Lightning research group at the University of Florida*, 2013.

[125] C. V. Boys, "Progressive lightning," ed: Nature Publishing Group, 1926.

[126] C. Boys, "Progressive lightning," *Nature,* vol. 122, no. 3070, pp. 310-311, 1928.

[127] C. Boys, "Progressive lightning," *Nature,* vol. 124, no. 3115, pp. 54-55, 1929.

[128] B. F. J. Schonland and H. Collens, "Progressive lightning," *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character,* vol. 143, no. 850, pp. 654-674, 1934.

[129] D. Malan and H. Collens, "Progressive lightning III—The fine structure of return lightning strokes," *Proceedings of the Royal Society of London. Series A-Mathematical and Physical Sciences,* vol. 162, no. 909, pp. 175-203, 1937.

[130] D. Malan and B. F. J. Schonland, "Progressive lightning. VII Directly-correlated photographic and electrical studies of lightning from near thunderstorms," *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences,* vol. 191, no. 1027, pp. 485-503, 1947.

[131] A. Andreotti, C. Petrarca, V. A. Rakov, and L. Verolino, "Calculation of voltages induced on overhead conductors by nonvertical lightning channels," *IEEE transactions on electromagnetic compatibility,* vol. 54, no. 4, pp. 860-870, 2011.

[132] C. Petrarca, S. Minucci, and A. Andreotti, "On the influence of channel tortuosity on electric fields generated by lightning return strokes at close distance," *Progress In Electromagnetics Research,* vol. 74, pp. 61-75, 2017.

[133] D. H. J. Christian, "A Lightning Primer," *Lightning and Atmospheric Electricity Research,* 2017.

[134] G. Medici, K. L. Cummins, D. J. Cecil, W. J. Koshak, and S. D. Rudlosky, "The intracloud lightning fraction in the contiguous United States," *Monthly Weather Review,* vol. 145, no. 11, pp. 4481-4499, 2017.

[135] S. Karunarathne, T. C. Marshall, M. Stolzenburg, and N. Karunarathna, "Observations of positive narrow bipolar pulses," *Journal of Geophysical Research: Atmospheres,* vol. 120, no. 14, pp. 7128-7143, 2015.

[136] D. M. Le Vine, "Sources of the strongest RF radiation from lightning," *Journal of Geophysical Research: Oceans,* vol. 85, no. C7, pp. 4091-4095, 1980.

[137] Z. Zakaria *et al.*, "Wavelet analysis of narrow bipolar pulses in tropical region," in *Electrical Engineering and Computer Science (ICECOS), 2017 International Conference on,* 2017: IEEE, pp. 280-284.

[138] T. Gunasekara, M. Fernando, U. Sonnadara, and V. Cooray, "Characteristics of Narrow Bipolar Pulses observed from lightning in Sri Lanka," *Journal of Atmospheric and Solar-Terrestrial Physics,* vol. 138, pp. 66-73, 2016.

[139] W. Rison *et al.*, "Observations of narrow bipolar events reveal how lightning is initiated in thunderstorms," *Nature communications,* vol. 7, p. 10721, 2016.

[140] T. Wu, S. Yoshida, T. Ushio, Z. Kawasaki, and D. Wang, "Lightning-initiator type of narrow bipolar events and their subsequent pulse trains," *Journal of Geophysical Research: Atmospheres,* vol. 119, no. 12, pp. 7425-7438, 2014.

[141] W. Rison *et al.*, "Observations of narrow bipolar events reveal how lightning is initiated in thunderstorms," *Nature communications,* vol. 7, no. 1, pp. 1-12, 2016.

[142] D. Suszcynsky and M. Heavner, "Narrow Bipolar Events as indicators of thunderstorm convective strength," *Geophysical research letters,* vol. 30, no. 17, 2003.

[143] M. M. Ismail, M. Rahman, V. Cooray, M. Fernando, P. Hettiarachchi, and D. Johari, "On the possible origin of chaotic pulse trains in lightning flashes," *Atmosphere,* vol. 8, no. 2, p. 29, 2017.

[144] C. D. Weidman, "The Submicrosecond Structure of Lightning Radiation Fields," 1982.

[145] N. A. Ahmad, "Broadband and HF radiation from cloud flashes and narrow bipolar pulses," Acta Universitatis Upsaliensis, 2011.

[146] Y. Lan, Y. j. Zhang, W. s. Dong, W. t. Lu, H. y. Liu, and D. Zheng, "Broadband analysis of chaotic pulse trains generated by negative cloud-to-ground lightning discharge," *Journal of Geophysical Research: Atmospheres,* vol. 116, no. D17, 2011.

[147] W. Zhou *et al.*, "Occurrence regularity of CPT discharge event in negative cloud-to-ground lightning," 2014.

[148] M. R. Ahmad, M. Esa, D. Johari, M. M. Ismail, and V. Cooray, "Chaotic pulse train in cloud-to-ground and cloud flashes of tropical thunderstorms," in *2014 International Conference On Lightning Protection (ICLP)*, 2014: IEEE, pp. 808-809.

[149] J. D. Hill, M. A. Uman, D. M. Jordan, J. R. Dwyer, and H. Rassoul, "“Chaotic” dart leaders in triggered lightning: Electric fields, X-rays, and source locations," *Journal of Geophysical Research: Atmospheres,* vol. 117, no. D3, 2012.

[150] Y. Zhang, Y. Zhang, C. Li, W. Lu, and D. Zheng, "Simultaneous optical and electrical observations of “chaotic” leaders preceding subsequent return strokes," *Atmospheric Research,* vol. 170, pp. 131-139, 2016.

[151] J. Mäkelä, M. Edirisinghe, M. Fernando, R. Montaño, and V. Cooray, "HF radiation emitted by chaotic leader processes," *Journal of Atmospheric and Solar-Terrestrial Physics,* vol. 69, no. 6, pp. 707-720, 2007.

[152] M. R. Ahmad, M. R. M. Esa, V. Cooray, and E. Dutkiewicz, "Interference from cloud-to-ground and cloud flashes in wireless communication system," *Electric Power Systems Research,* vol. 113, pp. 237-246, 2014.

[153] C. Bianchi and A. Meloni, "Natural and man-made terrestrial electromagnetic noise: an outlook," *Annals of geophysics,* 2007.

[154] F. Shi, N. Liu, J. R. Dwyer, and K. M. Ihaddadene, "VHF and UHF electromagnetic radiation produced by streamers in lightning," *Geophysical Research Letters,* vol. 46, no. 1, pp. 443-451, 2019.

[155] R. Zeng *et al.,* "Survey of recent progress on lightning and lightning protection research," *High Voltage,* vol. 1, no. 1, pp. 2-10, 2016.

[156] M. N. B. Hamzah, "Distinct Characteristics Of Cloud-To-Ground Lightning Electric Fields Generated In Malaysia," *Science,* 2015.

[157] C.-L. Wooi, Z. Abdul-Malek, N. A. Ahmad, M. R. M. Esa, Z. Zakaria, and M. R. Ahmad, "Wavelet analysis of chaotic pulse trains prior to subsequent return strokes in Malaysia," in *2016 33rd International Conference on Lightning Protection (ICLP)*, 2016: IEEE, pp. 1-6.

[158] C. Wagner and G. McCann, "Lightning phenomena: I—General characteristics," *Electrical Engineering,* vol. 60, no. 8, pp. 374-384, 1941.

[159] V. Rakov, "A review of positive and bipolar lightning discharges," *Bulletin of the American Meteorological Society,* vol. 84, no. 6, pp. 767-776, 2003.

[160] M. A. Uman, D. K. McLain, and E. P. Krider, "The electromagnetic radiation from a finite antenna," *American Journal of Physics,* vol. 43, no. 1, pp. 33-38, 1975.

[161] A. Nag, M. J. Murphy, K. L. Cummins, A. E. Pifer, and J. A. Cramer, "Recent evolution of the us National lightning detection network," in *Preprints, 23rd Int. Lightning Detection Conf., Tucson, AZ, Vaisala*, 2014.

[162] B. Kochtubajda and W. R. Burrows, "A decade of cloud-to-ground lightning in Canada: 1999–2008. Part 2: Polarity, multiplicity and first-stroke peak current," *Atmosphere-ocean,* vol. 48, no. 3, pp. 195-209, 2010.

[163] U. Sonnadara, V. Cooray, and T. Götschl, "Characteristics of cloud-to-ground lightning flashes over Sweden," *Physica scripta,* vol. 74, no. 5, p. 541, 2006.

[164] A. Weerasekera, D. Sonnadara, I. Fernando, J. Liyanage, R. Lelwala, and T. Ariyaratne, "Activity of cloud-to-ground lightning observed in Sri Lanka and

in surrounding area of the Indian Ocean," *Sri Lankan Journal of Physics,* vol. 2, 2001.

[165] O. Pinto Jr, I. Pinto, and K. Naccarato, "Maximum cloud-to-ground lightning flash densities observed by lightning location systems in the tropical region: A review," *Atmospheric Research,* vol. 84, no. 3, pp. 189-200, 2007.

[166] M. Ishii and J. I. Hojo, "Statistics on fine structure of cloud-to-ground lightning field waveforms," *Journal of Geophysical Research: Atmospheres,* vol. 94, no. D11, pp. 13267-13274, 1989.

[167] Y. Goto and K. I. Narita, "Electrical characteristics of winter lightning," *Journal of Atmospheric and Terrestrial Physics,* vol. 57, no. 5, pp. 449-458, 1995.

[168] Y. Tian *et al.,* "Characteristics of a bipolar cloud-to-ground lightning flash containing a positive stroke followed by three negative strokes," *Atmospheric Research,* vol. 176, pp. 222-230, 2016.

[169] A. Nag and V. A. Rakov, "Parameters of electric field waveforms produced by positive lightning return strokes," *IEEE Transactions on Electromagnetic Compatibility,* vol. 56, no. 4, pp. 932-939, 2014.

[170] P. B. Adhikari, S. Sharma, and K. Baral, "Features of positive ground flashes observed in Kathmandu Nepal," *Journal of Atmospheric and Solar-Terrestrial Physics,* vol. 145, pp. 106-113, 2016.

[171] C. Schumann, M. M. F. Saba, R. B. G. Da Silva, and W. Schulz, "Electric fields changes produced by positives cloud-to-ground lightning flashes," *Journal of Atmospheric and Solar-Terrestrial Physics,* vol. 92, pp. 37-42, 2013.

[172] D. Ma, "Characteristic pulse trains of preliminary breakdown in four isolated small thunderstorms," *Journal of Geophysical Research: Atmospheres,* vol. 122, no. 6, pp. 3361-3373, 2017.

[173] D. Johari, V. Cooray, M. Rahman, P. Hettiarachchi, and M. M. Ismail, "Characteristics of preliminary breakdown pulses in positive ground flashes during summer thunderstorms in Sweden," *Atmosphere,* vol. 7, no. 3, p. 39, 2016.

[174] M. M. Ismail, M. Rahman, V. Cooray, S. Sharma, P. Hettiarachchi, and D. Johari, "Electric field signatures in wideband, 3 MHz and 30 MHz of

negative ground flashes pertinent to Swedish thunderstorms," *Atmosphere*, vol. 6, no. 12, pp. 1904-1925, 2015.

[175] D. M. Fuquay, "Positive cloud-to-ground lightning in summer thunderstorms," *Journal of Geophysical Research: Oceans,* vol. 87, no. C9, pp. 7131-7140, 1982.

[176] M. M. Saba, L. Z. Campos, E. P. Krider, and O. Pinto, "High-speed video observations of positive ground flashes produced by intracloud lightning," *Geophysical Research Letters,* vol. 36, no. 12, 2009.

[177] M. Akita *et al.*, "Effects of charge distribution in thunderstorms on lightning propagation paths in Darwin, Australia," *Journal of the atmospheric sciences,* vol. 68, no. 4, pp. 719-726, 2011.

[178] L. Coleman, M. Stolzenburg, T. Marshall, and M. Stanley, "Horizontal lightning propagation, preliminary breakdown, and electric potential in New Mexico thunderstorms," *Journal of Geophysical Research: Atmospheres,* vol. 113, no. D9, 2008.

[179] L. Schwalt, S. Pack, W. Schulz, G. Diendorfer, and G. Pistotnik, "Number Of Single-Stroke Flashes In The Alpine Region Determined With A Video And Field Recording System," in *International Colloquium on Lightning and Power Systems (ICLP) 2017*, 2017.

[180] A. Hazmi, P. Emeraldi, M. I. Hamid, N. Takagi, and D. Wang, "Characterization of Positive Cloud to Ground Flashes Observed in Indonesia," *Atmosphere,* vol. 8, no. 1, p. 4, 2017.

[181] M. M. Saba *et al.*, "High-speed video observations of positive lightning flashes to ground," *Journal of Geophysical Research: Atmospheres,* vol. 115, no. D24, 2010.

[182] C. Schumann and M. M. Saba, "Continuing current intensity in positive ground flashes," in *Lightning Protection (ICLP), 2012 International Conference on*, 2012: IEEE, pp. 1-5.

[183] C. Romero, F. Rachidi, M. Rubinstein, M. Paolone, V. A. Rakov, and D. Pavanello, "Positive lightning flashes recorded on the Säntis tower from May 2010 to January 2012," *Journal of Geophysical Research: Atmospheres,* vol. 118, no. 23, 2013.

[184] M. Brook, M. Nakano, P. Krehbiel, and T. Takeuti, "The electrical structure of the Hokuriku winter thunderstorms," *Journal of Geophysical Research: Oceans,* vol. 87, no. C2, pp. 1207-1215, 1982.

[185] D. M. Romps, J. T. Seeley, D. Vollaro, and J. Molinari, "Projected increase in lightning strikes in the United States due to global warming," *Science,* vol. 346, no. 6211, pp. 851-854, 2014.

[186] C. Price and D. Rind, "Possible implications of global climate change on global lightning distributions and frequencies," *Journal of Geophysical Research: Atmospheres,* vol. 99, no. D5, pp. 10823-10831, 1994.

[187] T. Wu *et al.*, "Preliminary breakdown pulses of cloud-to-ground lightning in winter thunderstorms in Japan," *Journal of Atmospheric and Solar-Terrestrial Physics,* vol. 102, pp. 91-98, 2013.

[188] D. MacGorman, "Newsletter on Atmospheric Electricity," *16th International Conference on Atmospheric Electricity (ICAE),* vol. 28, no. 1, 2017.

[189] A. J. Dowdy, "Seasonal forecasting of lightning and thunderstorm activity in tropical and temperate regions of the world," *Scientific reports,* vol. 6, 2016.

[190] F. Wu, X. Cui, D.-L. Zhang, D. Liu, and D. Zheng, "SAFIR-3000 Lightning Statistics over the Beijing Metropolitan Region during 2005–07," *Journal of Applied Meteorology and Climatology,* vol. 55, no. 12, pp. 2613-2633, 2016.

[191] S. Hidayat and M. Ishii, "Spatial and temporal distribution of lightning activity around Java," *Journal of Geophysical Research: Atmospheres,* vol. 103, no. D12, pp. 14001-14009, 1998.

[192] R. J. Kane, "Lightning-rainfall relationships in an isolated thunderstorm over the mid-Atlantic states," *National Weather Digest,* vol. 17, no. 3, 1993.

[193] L. D. Carey and S. A. Rutledge, "The relationship between precipitation and lightning in tropical island convection: A C-band polarimetric radar study," *Monthly weather review,* vol. 128, no. 8, pp. 2687-2710, 2000.

[194] T. L. Bell, D. Rosenfeld, K. M. Kim, J. M. Yoo, M. I. Lee, and M. Hahnenberger, "Midweek increase in US summer rain and storm heights suggests air pollution invigorates rainstorms," *Journal of Geophysical Research: Atmospheres,* vol. 113, no. D2, 2008.

[195] B. R. Fuchs *et al.*, "Environmental controls on storm intensity and charge structure in multiple regions of the continental United States," *Journal of Geophysical Research: Atmospheres,* vol. 120, no. 13, pp. 6575-6596, 2015.

[196] S. Yoshida, T. Morimoto, T. Ushio, and Z. Kawasaki, "A fifth-power relationship for lightning activity from Tropical Rainfall Measuring Mission satellite observations," *Journal of Geophysical Research: Atmospheres,* vol. 114, no. D9, 2009.

[197] C. Gomes and V. Cooray, "Radiation field pulses associated with the initiation of positive cloud to ground lightning flashes," *Journal of atmospheric and solar-terrestrial physics,* vol. 66, no. 12, pp. 1047-1055, 2004.

[198] T. o. Ushio, Z. I. Kawasaki, K. Matsu-ura, and D. Wang, "Electric fields of initial breakdown in positive ground flash," *Journal of Geophysical Research: Atmospheres,* vol. 103, no. D12, pp. 14135-14139, 1998.

[199] M. Hamzah, M. Ab Kadir, C. Gomes, S. Arshad, N. Abdullah, and N. Hatta, "Unusually long duration lightning electric field return strokes in Malaysia," in *2014 International Conference on Lightning Protection (ICLP)*, 2014: IEEE, pp. 1691-1694.

[200] E. Jayaratne and Y. Kuleshov, "The relationship between lightning activity and surface wet bulb temperature and its variation with latitude in Australia," *Meteorology and Atmospheric Physics,* vol. 91, no. 1-4, pp. 17-24, 2006.

[201] P. Murugavel, S. Pawar, and V. Gopalakrishan, "Climatology of lightning over Indian region and its relationship with convective available potential energy," *International Journal of Climatology,* vol. 34, no. 11, pp. 3179-3187, 2014.

[202] S. Chaudhuri and A. Middey, "Disparity in the characteristic of thunderstorms and associated lightning activities over dissimilar terrains," *Meteorology and Atmospheric Physics,* vol. 119, no. 3, pp. 151-161, 2013.

[203] A. Dewan, E. T. Ongee, M. M. Rahman, R. Mahmood, and Y. Yamane, "Spatial and temporal analysis of a 17-year lightning climatology over Bangladesh with LIS data," *Theoretical and Applied Climatology,* vol. 134, no. 1, pp. 347-362, 2018.

[204] D. Royé, N. Lorenzo, and J. Martin-Vide, "Spatial–temporal patterns of cloud-to-ground lightning over the northwest Iberian Peninsula during the period 2010–2015," *Natural hazards,* vol. 92, no. 2, pp. 857-884, 2018.

[205] T. MathWorks, "History of Wavelets " *An Introduction to the Wavelet Families,* 2005.

[206] M. F. Wahab and T. C. O'Haver, "Wavelet transforms in separation science for denoising and peak overlap detection," *Journal of separation science,* vol. 43, no. 9-10, pp. 1998-2010, 2020.

[207] M. Van Berkel, "Wavelets for Feature Detection; Theoretical background," *no. March,* 2010.

[208] P. Vielva, E. Martínez-González, L. Cayón, J. Diego, J. Sanz, and L. Toffolatti, "Predicted Planck extragalactic point-source catalogue," *Monthly Notices of the Royal Astronomical Society,* vol. 326, no. 1, pp. 181-191, 2001.

[209] M. R. Islam, "Wavelets, its Application and Technique in signal and image processing," *Global Journal of Computer Science and Technology,* 2011.

[210] X. Mi, H. Ren, Z. Ouyang, W. Wei, and K. Ma, "The use of the Mexican Hat and the Morlet wavelets for detection of ecological patterns," *Plant Ecology,* vol. 179, no. 1, pp. 1-19, 2005.

[211] M. R. Shirani and F. Safi-Esfahani, "Dynamic scheduling of tasks in cloud computing applying dragonfly algorithm, biogeography-based optimization algorithm and Mexican hat wavelet," *The Journal of Supercomputing,* vol. 77, pp. 1214-1272, 2021.

[212] Z. Zhou and H. Adeli, "Time-frequency signal analysis of earthquake records using Mexican hat wavelets," *Computer-Aided Civil and Infrastructure Engineering,* vol. 18, no. 5, pp. 379-389, 2003.

[213] H. Guo, Q. He, and B. Jiang, "The application of Mexican Hat wavelet filtering and averaging algorithm in raman spectra denoising," in *2008 Congress on Image and Signal Processing,* 2008, vol. 4: IEEE, pp. 321-326.

[214] J. Gonzalez-Nuevo *et al.*, "The Mexican hat wavelet family: application to point-source detection in cosmic microwave background maps," *Monthly Notices of the Royal Astronomical Society,* vol. 369, no. 4, pp. 1603-1610, 2006.

[215] Š. Džakmić, T. Namas, and A. Husagić-Selman, "Combined Fourier transform and Mexican hat wavelet for fault detection in distribution networks," in *2017 9th IEEE-GCC Conference and Exhibition (GCCCE),* 2017: IEEE, pp. 1-6.

[216] K. Technologies, "User Manual for Software v0.30," *Chronos 1.4 High-Speed Camera,* vol. Document Revison 1, 2018.

[217] A. Few, "Power spectrum of thunder," *Journal of Geophysical Research,* vol. 74, no. 28, pp. 6926-6934, 1969.

[218] R. Hill, "Analysis of irregular paths of lightning channels," *Journal of Geophysical Research,* vol. 73, no. 6, pp. 1897-1906, 1968.

[219] Z.-k. Zhao and Q.-l. Zhang, "Influence of channel tortuosity on the lightning return stroke electromagnetic field in the time domain," *Atmospheric research,* vol. 91, no. 2-4, pp. 404-409, 2009.

[220] M. F. A. Galvan, "Operative Characteristics Of A Parallel-Plate Antenna To Measure Vertical Electric Field From Lightning Flashes," *Uppsala University,* 2000.

[221] S. Sharma, M. Fernando, and C. Gomes, "Signatures of electric field pulses generated by cloud flashes," *Journal of Atmospheric and Solar-Terrestrial Physics,* vol. 67, no. 4, pp. 413-422, 2005.

[222] Lumen, "Capacitors and Dielectrics," *Physics II: Electric Potential and Electric Field,* 2017.

[223] D. Sonnadara, C. Edirisinghe, and I. Fernando, "Construction of a High Speed Buffer Amplifier to Measure Lightning Generated Vertical Electric Fields," 2001.

[224] G. V. Cooray, *The lightning flash* (no. 34). Iet, 2003.

[225] M. A. Uman, *The lightning discharge*. Courier Corporation, 2001.

[226] H. E. Rojas, C. A. Rivera, J. Chaves, C. A. Cortés, F. J. Román, and M. Fernando, "New circuit for the measurement of lightning generated electric fields," in *2017 International Symposium on Lightning Protection (XIV SIPDA),* 2017: IEEE, pp. 188-194.

[227] P. Power, "RG58 Coaxial Cable Datasheet," 2016.

[228] I. Teledyne LeCroy, "HDO4000A High Definition Oscilloscopes (200 MHz - 1 GHz) Datasheet," *Debug In High Definition* 2019

[229] P. Technology, "PicoScope 5000D Series Datasheet," *FlexRes oscilloscopes and MSOs,* 2018.

[230] J. Patel, "Regular grounding measurements can be made without taking equipment offline," *Test and Measurement: Earth Ground Resistance Testing can Improve Uptime,* 2017.

[231] L. Kyoritsu Electrical Instruments Works, "Multi-Function Tester (KEW 6016)," *Instruction Manual* 2019.

[232] A. G. a. M. Fernando, "Operative Characteristics Of A Parallel-Plate Antenna To Measure Vertical Electric Field From Lightning Flashes," *Uppsala University*, 2000.

[233] A. Nag and V. A. Rakov, "Pulse trains that are characteristic of preliminary breakdown in cloud-to-ground lightning but are not followed by return stroke pulses," *Journal of Geophysical Research: Atmospheres*, vol. 113, no. D1, 2008.

[234] K. S. Clifton and C. K. Hill, "Low-light-level television measurements of lightning," *Bulletin of the American Meteorological Society*, vol. 61, no. 9, pp. 987-992, 1980.

[235] Atmo, "subsequent return strokes," *Multiple strokes flashes - dart leaders and subsequent return strokes*, 2018

[236] P. Pohl, "Lightning Physics: Subsequent Strokes," *Austrian Lightning Detection and Information System, Lightning Research*, 2019.

[237] A. Nag and V. A. Rakov, "Positive lightning: An overview, new observations, and inferences," *Journal of Geophysical Research: Atmospheres*, vol. 117, no. D8, 2012.

[238] V. Cooray, *An introduction to lightning*. Springer, 2015.

[239] L. Schwalt, S. Pack, W. Schulz, and G. Pistotnik, "Percentage of single-stroke flashes related to different thunderstorm types," *Electric Power Systems Research*, vol. 194, p. 107109, 2021.

[240] V. A. Rakov and G. R. Huffines, "Return-stroke multiplicity of negative cloud-to-ground lightning flashes," *Journal of Applied Meteorology*, vol. 42, no. 10, pp. 1455-1462, 2003.

[241] O. Pinto Jr, I. R. C. Pinto, J. H. Diniz, A. Cazetta Filho, L. C. Cherchiglia, and A. M. Carvalho, "A seven-year study about the negative cloud-to-ground lightning flash characteristics in Southeastern Brazil," *Journal of Atmospheric and Solar-Terrestrial Physics*, vol. 65, no. 6, pp. 739-748, 2003.

[242] C. Crozier, H. Herscovitch, and J. Scott, "Some observations and characteristics of lightning ground discharges in southern Ontario," *Atmosphere-Ocean*, vol. 26, no. 3, pp. 399-436, 2010.

[243] J. P. Rafferty, *Storms, Violent Winds, and Earth's Atmosphere*. Britannica Educational Publishing, 2010.

[244] C. Peng *et al.*, "Observations of single-stroke flashes from five isolated small thunderstorms in East China," *Journal of Atmospheric and Solar-Terrestrial Physics,* vol. 211, p. 105441, 2020.

[245] M. Saba, M. Ballarotti, and O. Pinto Jr, "Negative cloud-to-ground lightning properties from high-speed video observations," *Journal of Geophysical Research: Atmospheres,* vol. 111, no. D3, 2006.

[246] W. C. Valine and E. P. Krider, "Statistics and characteristics of cloud-to-ground lightning with multiple ground contacts," *Journal of Geophysical Research: Atmospheres,* vol. 107, no. D20, pp. AAC 8-1-AAC 8-11, 2002.

[247] X. Kong, X. Qie, Y. Zhao, and T. Zhang, "Characteristics of negative lightning flashes presenting multiple-ground terminations on a millisecond-scale," *Atmospheric Research,* vol. 91, no. 2-4, pp. 381-386, 2009.

[248] M. Stolzenburg, T. C. Marshall, and S. Karunarathne, "Inception of subsequent stepped leaders in negative cloud-to-ground lightning," *Meteorology and Atmospheric Physics,* vol. 132, no. 4, pp. 489-514, 2020.

[249] N. Kitagawa, M. Brook, and E. Workman, "Continuing currents in cloud-to-ground lightning discharges," *Journal of Geophysical Research,* vol. 67, no. 2, pp. 637-647, 1962.

[250] Z. Sun, X. Qie, M. Liu, R. Jiang, Z. Wang, and H. Zhang, "Characteristics of a negative lightning with multiple-ground terminations observed by a VHF lightning location system," *Journal of Geophysical Research: Atmospheres,* vol. 121, no. 1, pp. 413-426, 2016.

[251] J. Willett, D. Le Vine, and V. Idone, "Lightning-channel morphology revealed by return-stroke radiation field waveforms," *Journal of Geophysical Research: Atmospheres,* vol. 100, no. D2, pp. 2727-2738, 1995.

[252] D. Wang, N. Takagi, T. Watanabe, V. Rakov, and M. Uman, "Luminosity waves in branched channels of two negative lightning flashes," *J. Atmos. Electr,* vol. 20, no. 2, pp. 91-97, 2000.

[253] R. Scientist, "UCSB ScienceLine: Why lightning split?," *University of California, Santa Barbara,* 2002.

[254] X.-J. Wang, P. Yuan, J.-Y. Cen, J. Wang, and T.-L. Zhang, "Study on the conductivity properties of lightning channel by spectroscopy," *Spectroscopy and Spectral Analysis,* vol. 33, no. 12, pp. 3192-3196, 2013.

[255] X. Chang, P. Yuan, J. Cen, and X. Wang, "Variation of the channel temperature in the transmission of lightning leader," *Journal of Atmospheric and Solar-Terrestrial Physics,* vol. 159, pp. 41-47, 2017.

[256] N. Zhang, P. Yuan, T. ting An, M. Zhang, and R. rong Chen, "The conductivity and propagation property of lightning leader tip," *Atmospheric Research,* vol. 245, p. 105099, 2020.

[257] Q. LIYANGHUANG, L. YUNLI, C. GAO, J. WANG, and F. GUO, "Correlation of Charge Distribution Among Different Branches in a Natural Lightning Flash."

[258] T. A. Warner, R. E. Orville, J. Marshall, and K. Huggins, "Spectral (600–1050 nm) time exposures (99.6 μs) of a lightning stepped leader," *Journal of Geophysical Research: Atmospheres,* vol. 116, no. D12, 2011.

[259] R. Jiang *et al.*, "Channel branching and zigzagging in negative cloud-to-ground lightning," *Scientific reports,* vol. 7, no. 1, p. 3457, 2017.

[260] G. A. Wurden and D. Whiteson, "High-speed plasma imaging: a lightning bolt," *IEEE transactions on plasma science,* vol. 24, no. 1, pp. 83-84, 1996.

[261] G. Maslowski and P. Baranski, "Natural Lightning Channel Evolution Obtained From High-Speed Digital Video Camera Recordings," *Publs. Inst. Geophys. Pol. Acad. Sc., Monographic,* vol. 73, no. 412, pp. 99-107, 2009.

[262] C. Wang, Z. Sun, R. Jiang, Y. Tian, and X. Qie, "Characteristics of downward leaders in a cloud-to-ground lightning strike on a lightning rod," *Atmospheric Research,* vol. 203, pp. 246-253, 2018.

[263] L. Antunes *et al.*, "Characterization of lightning observed by multiple high-speed cameras," in *2013 International Symposium on Lightning Protection (XII SIPDA)*, 2013: IEEE, pp. 17-25.

[264] J. M. Livingston and E. P. Krider, "Electric fields produced by Florida thunderstorms," *Journal of Geophysical Research: Oceans,* vol. 83, no. C1, pp. 385-401, 1978.

[265] V. Mazur, P. R. Krehbiel, and X. M. Shao, "Correlated high-speed video and radio interferometric observations of a cloud-to-ground lightning flash," *Journal of Geophysical Research: Atmospheres,* vol. 100, no. D12, pp. 25731-25753, 1995.

[266] V. A. Rakov and M. A. Uman, "Long continuing current in negative lightning ground flashes," *Journal of Geophysical Research: Atmospheres,* vol. 95, no. D5, pp. 5455-5470, 1990.

[267] J. Li, S. Cummer, W. Lyons, and T. Nelson, "Coordinated analysis of delayed sprites with high-speed images and remote electromagnetic fields," *Journal of Geophysical Research: Atmospheres,* vol. 113, no. D20, 2008.

[268] J. Podur, D. L. Martell, and F. Csillag, "Spatial patterns of lightning-caused forest fires in Ontario, 1976–1998," *Ecological modelling,* vol. 164, no. 1, pp. 1-20, 2003.

[269] M. Larjavaara, J. Pennanen, and T. Tuomi, "Lightning that ignites forest fires in Finland," *Agricultural and Forest Meteorology,* vol. 132, no. 3-4, pp. 171-180, 2005.

[270] F. A. Fisher and J. A. Plumer, "Lightning protection of aircraft," 1977.

[271] F. L. Kester, M. Gerstein, and J. Plumer, "A Study of Aircraft Fire Hazards Related to Natural Electrical Phenomena," 1960.

[272] M. Uman and V. Rakov, "The interaction of lightning with airborne vehicles," *Progress in Aerospace Sciences,* vol. 39, no. 1, pp. 61-81, 2003.

[273] H. Maghsoudi, Y. Adyani, and N. Ahmadian, "Electrical and lightning injuries," *Journal of burn care & research,* vol. 28, no. 2, pp. 255-261, 2007.

[274] S.-j. Yang *et al.*, "Characteristics analysis of the induced overcurrent generated by close triggered lightning on the overhead transmission power line," *Journal of Tropical Meteorology,* vol. 16, no. 1, p. 59, 2010.

[275] R. B. B. Gin, A. J. Pereira Filho, and C. Beneti, "A. Long continuing luminosity of cloud-to-ground flashes observations at urban area, Brazil," in *13th International Conference on Atmospheric Electricity, Beijing, China. Anais*, 2007.

[276] K. Asmaini, "Expect More storms, heavy rain," *New Straits Times,* 2019.

[277] A. Esmail, "Warning: Expect Flash Floods to Hit Beginning 19 March Due to Monsoon Transition Phase," *World Of Buzz,* 2019.

[278] J. Diebel, "Average Weather " *Average Weather Malaysia by WeatherSpark,* 2020. [Online]. Available: https://weatherspark.com.

[279] M. Sato and H. Fukunishi, "Global sprite occurrence locations and rates derived from triangulation of transient Schumann resonance events," *Geophysical Research Letters*, vol. 30, no. 16, 2003.

[280] G. Elert, "Electric Current," *The Physics Hypertextbook*, 2018.

[281] R. B. B. Gin, C. A. A. Beneti, M. Jusevicius, and A. Pereira Filho, "High Peak Current In Long Continuing Luminosity Of Positive Flashes: A Case Study," 2010.

[282] T. A. Warner, "Positive and Negative Leaders Behave Differently," *Education*, 2019.

[283] M. M. Saba *et al.*, "Positive leader characteristics from high-speed video observations," *Geophysical Research Letters*, vol. 35, no. 7, 2008.

[284] A. Saraiva, M. Saba, O. Pinto Jr, K. Cummins, E. Krider, and L. Campos, "A comparative study of negative cloud-to-ground lightning characteristics in São Paulo (Brazil) and Arizona (United States) based on high-speed video observations," *Journal of Geophysical Research: Atmospheres*, vol. 115, no. D11, 2010.

[285] Y. Li, L. Shi, S. Qiu, Y. Duan, Z. Sun, and T. Wang, "Observation results and discussion on an upward leader followed by a long continuing current after a return stroke," *Geophysical Research Letters*, vol. 45, no. 14, pp. 7213-7217, 2018.

[286] M. A. Uman and R. E. Voshall, "Time interval between lightning strokes and the initiation of dart leaders," *Journal of Geophysical Research*, vol. 73, no. 2, pp. 497-506, 1968.

[287] S. A. Cummer and M. Füllekrug, "Unusually intense continuing current in lightning produces delayed mesospheric breakdown," *Geophysical Research Letters*, vol. 28, no. 3, pp. 495-498, 2001.

[288] E. Zhou, W. Lu, Y. Zhang, B. Zhu, D. Zheng, and Y. Zhang, "Correlation analysis between the channel current and luminosity of initial continuous and continuing current processes in an artificially triggered lightning flash," *Atmospheric research*, vol. 129, pp. 79-89, 2013.

[289] M. A. Uman, "Natural lightning," *IEEE transactions on industry applications*, vol. 30, no. 3, pp. 785-790, 1994.

[290] T. A. Warner, "Observations of simultaneous upward lightning leaders from multiple tall structures," *Atmospheric research*, vol. 117, pp. 45-54, 2012.

[291] A. Wada, A. Asakawa, T. Shindo, and S. Yokoyama, "Leader and return stroke speed of upward-initiated lightning," in *Proc. of 10th International Conference on Atmospheric Electricity*, 2003, pp. 553-556.

[292] M. M. Ismail, "Features and Origin of Electromagnetic Fields Generated by Lightning Flashes," *Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology 1535.*, p. 54 pp, 2017.

[293] M. M. Ismail, "Features and origin of electromagnetic fields generated by lightning flashes," Acta Universitatis Upsaliensis, 2017.

[294] C.-L. Wooi, Z. Abdul-Malek, M. N. K. H. Rohani, S. N. M. Arshad, and A. M. B. Yusof, "Techniques for Analysis of Chaotic Pulse Trains Generated by Lightning: A Review," in *2018 International Conference on Electrical Engineering and Computer Science (ICECOS)*, 2018: IEEE, pp. 259-264.

[295] Y. Pu, X. Qie, R. Jiang, Z. Sun, M. Liu, and H. Zhang, "Broadband characteristics of chaotic pulse trains associated with sequential dart leaders in a rocket-triggered lightning flash," *Journal of Geophysical Research: Atmospheres*, vol. 124, no. 7, pp. 4074-4085, 2019.

[296] V. Cooray, G. Cooray, T. Marshall, S. Arabshahi, J. Dwyer, and H. Rassoul, "Electromagnetic fields of a relativistic electron avalanche with special attention to the origin of lightning signatures known as narrow bipolar pulses," *Atmospheric research*, vol. 149, pp. 346-358, 2014.

[297] J. Willett, J. Bailey, and E. Krider, "A class of unusual lightning electric field waveforms with very strong high-frequency radiation," *Journal of Geophysical Research: Atmospheres*, vol. 94, no. D13, pp. 16255-16267, 1989.

[298] L. MD, "Frequency Bands and Applications," *Antenna Development*, 2020.

[299] A. Helwig, G. Offermans, C. Schue, B. Walker, T. Hardy, and K. Zwicker, "Low frequency (LF) solutions for alternative positioning, navigation, timing, and data (APNT&D) and associated receiver technology," in *Proceedings of the 2011 International Technical Meeting of the Institute of Navigation*, 2011, pp. 206-222.

[300] S. T. Maguire and P. A. Robertson, "Low frequency radio polarization sensor with applications in attitude estimation," *IEEE Sensors Journal*, vol. 15, no. 12, pp. 7304-7311, 2015.

[301] B. Schweber, "Understanding Antenna Specifications and Operation, Part 1," *Antenna fundamentals*, 2017.

[302] J. Li, B. Whisner, and J. A. Waynert, "Measurements of medium-frequency propagation characteristics of a transmission line in an underground coal mine," *IEEE Transactions on Industry Applications,* vol. 49, no. 5, pp. 1984-1991, 2013.

[303] D. E. Brocker, P. E. Sieber, P. L. Werner, and D. H. Werner, "A hybrid approach for large-scale optimizations of medium frequency propagation in coal mines," in *2011 IEEE International Symposium on Antennas and Propagation (APSURSI)*, 2011: IEEE, pp. 2391-2394.

[304] M. A. B. Yusof and S. Kabir, "An overview of sonar and electromagnetic waves for underwater communication," *IETE Technical Review,* vol. 29, no. 4, pp. 307-317, 2012.

[305] T. E. o. E. Britannica, "Communications: Radio-frequency spectrum," *Encyclopædia Britannica,* 2013.

[306] D. Robinson, "Lightning Types and Classifications," *In-depth look at cloud-to-ground lightning,* 2015.

[307] R. Nave, "Voltage," *Hyperphysics: Electricity and magnetism,* 2000.

[308] A. S. Kusim, "An Electro-magnetic Transient (EMT) Analysis on a 132 KV Rated Cu/XLPE/SCW/MDPE Cable System and Its Related Networks," Universiti Teknologi Malaysia, 2009.

[309] N. I. Ahmad, Z. Ali, M. Z. A. Ab. Kadir, M. Osman, N. H. Zaini, and M. H. Roslan, "Impacts of lightning-induced overvoltage on a hybrid solar PV–battery energy storage system," *Applied Sciences,* vol. 11, no. 8, p. 3633, 2021.

[310] X. Liu, M. Zhang, T. Wang, and Y. Ge, "Fast evaluation of lightning-induced voltages of overhead line and buried cable considering the lossy ground," *IET Science, Measurement & Technology,* vol. 13, no. 1, pp. 67-73, 2019.

[311] Lumen, "Electric Power and Energy," *Boundless Physics: Energy Usage,* 2013.

[312] V. Rakov *et al.*, "CIGRE technical brochure on lightning parameters for engineering applications," in *2013 International Symposium on Lightning Protection (XII SIPDA)*, 2013: IEEE, pp. 373-377.

[313] C.-L. Wooi, Z. Abdul-Malek, N.-A. Ahmad, and A. I. El Gayar, "Statistical analysis of electric field parameters for negative lightning in Malaysia,"

Journal of Atmospheric and Solar-Terrestrial Physics, vol. 146, pp. 69-80, 2016.

[314] A. Sharma, "Is n = 30 really enough? A popular inductive fallacy among data analysts.," *Towards Data Science,* 2020.

[315] A. Ganti, "Central Limit Theorem (CLT). 13 September," ed, 2019.

[316] M. A. Bahari, Z. A. Baharudin, T. Sutikno, A. I. A. Rahman, M. A. M. Hanafiah, and M. Ibrahim, "An analysis of manual and autoanalysis for submicrosecond parameters in the typical first lightning return stroke," *Indonesian Journal of Electrical Engineering and Computer Science,* vol. 23, no. 3, pp. 1451-1457, 2021.

[317] K. Mehranzamir, Z. Abdul-Malek, B. Salimi, and N. A. Ahmad, "Return strokes measurements of electric field produced by lightning discharges in Malaysia," in *Applied Mechanics and Materials*, 2014, vol. 554: Trans Tech Publ, pp. 618-622.

[318] B. Salimi, Z. Abdul-Malek, K. Mehranzamir, and N. A. Ahmad, "Study on the Vertical Component of Lightning Electric Field during Monsoon Period in Malaysia," in *Applied Mechanics and Materials*, 2014, vol. 554: Trans Tech Publ, pp. 623-627.

[319] A. Nag and K. L. Cummins, "Negative first stroke leader characteristics in cloud-to-ground lightning over land and ocean," *Geophysical Research Letters,* vol. 44, no. 4, pp. 1973-1980, 2017.

[320] A. Nag and K. L. Cummins, "Magnetic field risetimes of negative lightning first return strokes over land and ocean," *Geophysical Research Letters,* vol. 45, no. 23, pp. 13,133-13,141, 2018.

[321] R. Said, M. Cohen, and U. Inan, "Highly intense lightning over the oceans: Estimated peak currents from global GLD360 observations," *Journal of Geophysical Research: Atmospheres,* vol. 118, no. 13, pp. 6905-6915, 2013.

[322] I. Lukačovič, "Andaman Sea, Asia," *Weather forecast and live wind map,* 2019. [Online]. Available: https://windy.app.

[323] J. Diebel, "Average Weather," *Average Weather Malaysia by WeatherSpark,* 2020. [Online]. Available: https://weatherspark.com.

[324] Q. Ding, "A mathematical model for reflection of electromagnetic wave," in *Journal of Physics: Conference Series*, 2019, vol. 1213, no. 4: IOP Publishing, p. 042077.

[325] G. Lu, S. A. Cummer, R. J. Blakeslee, S. Weiss, and W. H. Beasley, "Lightning morphology and impulse charge moment change of high peak current negative strokes," *Journal of Geophysical Research: Atmospheres*, vol. 117, no. D4, 2012.

[326] V. Rakov and A. Dulzon, "A modified transmission line model for lightning return stroke field calculations," in *Proc. 9th Int. Symp. Electromagn. Compat*, 1991, pp. 229-235.

[327] V. Cooray, "A model for subsequent return strokes," *Journal of Electrostatics*, vol. 30, pp. 343-354, 1993.

[328] Y. Zhang, H. Pang, B. Liu, Q. Zhang, L. Song, and X. Lu, "Propagation effect of the lightning electric fields along rough sea surface and the effects on ToA-based lightning location systems," *International Journal of Applied Electromagnetics and Mechanics*, vol. 57, no. 4, pp. 415-425, 2018.

[329] Q. Zhang, J. Yang, D. Li, and Z. Wang, "Propagation effects of a fractal rough ocean surface on the vertical electric field generated by lightning return strokes," *Journal of electrostatics*, vol. 70, no. 1, pp. 54-59, 2012.

[330] C. Paul, F. H. Heidler, and W. Schulz, "Current and Electric Field Characteristics of 35 Return Strokes from Negative Lightning Measured at Peissenberg Tower Germany," in *The International Symposium on High Voltage Engineering*, 2019: Springer, pp. 1169-1179.

[331] S. Hidayat and M. Ishii, "Lightning discharges on land and on sea in Indonesia," in *2006 IEEE 8th International Conference on Properties & applications of Dielectric Materials*, 2006: IEEE, pp. 315-318.

[332] D. Li *et al.*, "Analysis of lightning electromagnetic field propagation in mountainous terrain and its effects on ToA-based lightning location systems," *Journal of Geophysical Research: Atmospheres*, vol. 121, no. 2, pp. 895-911, 2016.

[333] J. Frost, "Guidelines for Removing and Handling Outliers in Data," *Statistics By Jim*, 2020.

[334] Q. Zhang, J. Yang, X. Jing, D. Li, and Z. Wang, "Propagation effect of a fractal rough ground boundary on the lightning-radiated vertical electric field," *Atmospheric research*, vol. 104, pp. 202-208, 2012.

[335] Q. Zhang, X. Jing, J. Yang, D. Li, and X. Tang, "Numerical simulation of the lightning electromagnetic fields along a rough and ocean-land mixed

propagation path," *Journal of Geophysical Research: Atmospheres,* vol. 117, no. D20, 2012.

[336] J. L. Canty, "Sibu Weather," *Sibu Climate Summary by Weatherbase,* 2020. [Online]. Available: https://www.weatherbase.com/weather/weather-summary.php3?s=12469&cityname=Sibu%2C+Sarawak%2C+Malaysia&units=.

[337] I. Pinto, O. Pinto Jr, R. Rocha, J. Diniz, A. Carvalho, and A. C. Filho, "Cloud-to-ground lightning in southeastern Brazil in 1993: 2. Time variations and flash characteristics," *Journal of Geophysical Research: Atmospheres,* vol. 104, no. D24, pp. 31381-31387, 1999.

[338] K. Miyake, T. Suzuki, and K. Shinjou, "Characteristics of winter lightning current on Japan Sea coast," *IEEE Transactions on power Delivery,* vol. 7, no. 3, pp. 1450-1457, 1992.

[339] D. Zheng, Y. Zhang, Q. Meng, L. Chen, and J. Dan, "Climatological comparison of small-and large-current cloud-to-ground lightning flashes over Southern China," *Journal of Climate,* vol. 29, no. 8, pp. 2831-2848, 2016.

[340] T. Chronis *et al.*, "Climatological diurnal variation of negative CG lightning peak current over the continental United States," *Journal of Geophysical Research: Atmospheres,* vol. 120, no. 2, pp. 582-589, 2015.

[341] C. D. Ahrens, *Meteorology today: an introduction to weather, climate, and the environment*. Cengage Learning, 2012.

[342] M. G. Lawrence, "The relationship between relative humidity and the dewpoint temperature in moist air: A simple conversion and applications," *Bulletin of the American Meteorological Society,* vol. 86, no. 2, pp. 225-234, 2005.

[343] G. Jones, "Sunrise and Sunset in Malaysia," *Time and Date: Sun and Moon,* 2017. [Online]. Available: https://www.timeanddate.com/weather/malaysia/sibu/.

[344] G. V. Cooray, *TheLightning Flash* (no. 34). Iet, 2003.

[345] Y. Wang *et al.*, "Beijing Lightning Network (BLNET) and the observation on preliminary breakdown processes," *Atmospheric Research,* vol. 171, pp. 121-132, 2016.

[346] J. S. Mäkelä, N. Porjo, A. Mäkelä, T. Tuomi, and V. Cooray, "Properties of preliminary breakdown processes in Scandinavian lightning," *Journal of*

atmospheric and solar-terrestrial physics, vol. 70, no. 16, pp. 2041-2052, 2008.

[347] Y. Zhu, V. A. Rakov, and M. D. Tran, "A study of preliminary breakdown and return stroke processes in high-intensity negative lightning discharges," *Atmosphere*, vol. 7, no. 10, p. 130, 2016.

[348] C. Gomes, V. Cooray, and C. Jayaratne, "Comparison of preliminary breakdown pulses observed in Sweden and in Sri Lanka," *Journal of atmospheric and solar-terrestrial physics*, vol. 60, no. 10, pp. 975-979, 1998.

[349] Y. Zhu, V. A. Rakov, S. Mallick, and M. D. Tran, "Characterization of negative cloud-to-ground lightning in Florida," *Journal of Atmospheric and Solar-Terrestrial Physics*, vol. 136, pp. 8-15, 2015.

[350] Y. Zhu, V. Rakov, S. Mallick, M. Tran, J. Pilkey, and M. Uman, "Preliminary breakdown pulse trains in electric field records of negative cloud-to-ground lightning," in *XV International Conference on Atmospheric Electricity*, 2014, pp. 15-20.

[351] M. R. Ahmad, M. R. M. Esa, V. Cooray, Z. A. Baharudin, and P. Hettiarachchi, "Latitude dependence of narrow bipolar pulse emissions," *Journal of Atmospheric and Solar-Terrestrial Physics*, vol. 128, pp. 40-45, 2015.

[352] S. M. Arshad *et al.*, "Characterization preliminary breakdown in the measured lightning electric fields," in *2014 IEEE 8th International Power Engineering and Optimization Conference (PEOCO2014)*, 2014: IEEE, pp. 435-438.

LIST OF PUBLICATIONS

Journal with Impact Factor

1. **N. A. Ramlee,** N. Ahmad, Z. Baharudin, and A. Mohamed, "High-Speed video observations on fork lightning events in Malaysia," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 19, no. 3, pp. 1620-1625, 2020. **(Q3, IF: 0.24)**

Indexed Conference Proceedings (Indexed by SCOPUS)

1. **N. A. Ramlee,** N. Ahmad, M. Esa, Z. Malek, Z. Adzis, and Z. Nordeen, "Characteristics of Positive Lightning as Observed in Temperate and Tropic Regions: A Review," in *2018 2nd International Conference on Electrical Engineering and Informatics (ICon EEI)*, 2018: IEEE, pp. 159-164.

2. **N. A. Ramlee,** N. A Ahmad, Z. A. Baharudin, "Lightning Measurement in Sarawak, Malaysia: First Results," in *2021 3rd International Youth Conference on Radio Electronics, Electrical and Power Engineering*, 2021: IEEE, pp. 1-6.

Non-indexed Journal

1. **N. A. Ramlee**, N. A Ahmad, Z. A. Baharudin, "Characteristics of Diurnal and Nocturnal Lightning Activities in Sarawak, Malaysia," *Borneo Journal of Sciences & Technology*, vol. 3, no. 1, pp. 43-50, 2021, doi: 10.3570/bjost.2021.3.1-07.

In Press

1. **N. A. Ramlee**, N. A Ahmad, Z. A. Baharudin, “First-Time High-Speed Video Observations of Negative Lightning Return Strokes in Universiti Teknikal Malaysia Malacca, Malaysia.” *4th International Symposium on Lightning Research (ISLR 2019).*

2. **N. Asrina Ramlee**, N. A Ahmad, Z. A. Baharudin, M.R. M. Esa, "Temporal Analysis on Pulse Train of Lightning Discharge Observed in Malacca, Malaysia" *Special issue of 2022 9th International Conference on Power and Energy Systems Engineering (CPESE 2022) with Energy Reports.* **(Q1, IF: 6.87)**