UNIVERSITI PUTRA MALAYSIA

DISTINCT CHARACTERISTICS OF CLOUD-TO-GROUND LIGHTNING ELECTRIC FIELDS GENERATED IN MALAYSIA

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By

MUHAMMAD NOH BIN HAMZAH

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

June 2015

I dedicate this thesis to Allah, his messenger Muhammad S.A.W. and my beloved family

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

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By

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June 2015

Chair: Mohd Zainal Abidin bin Ab. Kadir, PhD

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Lightning generates electric fields that propagate through the vicinity of the atmosphere that have negative consequences especially to power, electronic and communications systems. Knowledge to the types of lightning and their characteristics must be acquired to fulfil the task of mitigating lightning problems. Most studies regarding the topic were done in temperate and sub-tropic regions. Thus, this study seeks to uncover better understanding of the lightning generated electric fields of cloud-to-ground lightning flashes observed in Malaysia in the tropics. Measurements of the generated fields were done using parallel plate antenna coupled with a recording system during the months of May, June and October 2013 at the premises of Universiti Putra Malaysia. The measurement site has a geographical coordinate of 2°59'19.9"N latitude and 101°43'29.8"E longitude, situated in Serdang, Selangor area. Malaysia generally has a tropical climate with maximum monsoon rain occurring from October due to southwest monsoon and intermonsoon period which affects the Selangor. The locations of some of the flashes were obtained from the Tenaga Nasional Berhad Research which is a research centre for the largest local power utility company, Tenaga Nasional Berhad using their Fault Analysis and Lightning Location System.

This thesis presents the characteristics of lightning generated vertical electric field waveforms recorded in Malaysia. A total of 115 negative lightning and 57 positive lightning found with preliminary breakdown pulses, return strokes and chaotic pulse trains were present and analysed. The main findings of this study include characteristics of preliminary breakdown pulses, unusually long duration return strokes lasting more than 1 ms per stroke, occurrence of positive lightning and chaotic pulse trains in Malaysia with average durations of 335.12 μs for both negative and positive lightning combined, high multiplicity of positive lightning return strokes having an average multiplicity of 3.86, short interstroke intervals of positive lightning with an arithmetic mean of 25.03 ms, occurrence of chaotic pulse trains in positive lightning and unusual occurrences of chaotic pulse trains in terms of their placement in both types of lightning. In conclusion, the findings of the electric field generated in Malaysia were found to be distinct in many ways that adds to new knowledge from the findings previously mentioned. This is important as the kind of lightning activity affects the way in which protection systems are made.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

CIRI-CIRI BERBEZA MEDAN ELEKTRIK KILAT AWAN-KE-TANAH YANG DIJANA DI MALAYSIA

Oleh

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Kilat menjana medan elektrik yang disebarkan melalui atmosfera mempunyai kesan negatif terutamanya kepada sistem kuasa, elektronik dan komunikasi. Pengetahuan mengenai jenis kilat dan ciri-cirinya mesti dipelajari untuk memenuhi tugas mengurangkan masalah-masalah berkenaan kilat. Kebanyakan kajian mengenai topik ini telah pun dilakukan di kawasan iklim sederhana dan sub-tropika. Oleh itu, kajian ini bertujuan untuk mendedahkan pemahaman yang lebih baik tentang medan elektrik yang dihasilkan oleh pancaran kilat awan-ke-tanah yang diperhatikan di Malaysia di kawasan tropika. Pengukuran medan elektrik yang dihasilkan dalam kajian ini telah dilakukan dengan menggunakan antena plat selari bersama dengan sistem rakaman pada bulan Mei, Jun dan Oktober 2013 di premis Universiti Putra Malaysia. Tapak pengukuran berada pada kedudukan geografi dengan latitud 2°59'19.9"U dan longitud 101°43'29.8"T yang terletak di kawasan Serdang, Selangor. Malaysia secara amnya mempunyai iklim tropika dengan hujan maksimum berlaku pada bulan Oktober oleh monsun barat daya dan musim pertukaran monsun yang melibatkan kawasan Selangor. Lokasi beberapa kilat diperolehi dari TNBR yang merupakan pusat penyelidikan bagi syarikat utiliti tenaga tempatan terbesar, TNB menggunakan system analisis kerosakan dan lokasi kilat mereka.

Tesis ini membentangkan ciri-ciri gelombang medan elektrik tegak yang dijana kilat direkodkan di Malaysia. Sejumlah 115 kilat negatif dan 57 kilat positif didapati dengan denyut pecahan awal, panahan balik dan rangkaian denyut camuk didapati hadir dan dianalisis. Dapatan utama kajian ini termasuk keputusan ciri-ciri denyut pecahan awal, tempoh luar biasa panjang panahan balik yang memakan masa lebih dari 1 ms setiap panahan, berlakunya kilat positif dan rangkaian denyut camuk di Malaysia dengan purata masa 335.12 µs untuk kilat negatif dan positif digabungkan, purata gandaan tinggi panahan balik kilat positif dengan purata gandaan 3.86, selang pendek antara panahan balik kilat positif dengan purata aritmetik 25.03 ms, berlakunya rangkaian denyut camuk dalam kilat positif dan kejadian luar biasa rangkaian denyut camuk dari segi kedudukan mereka dalam kilat positif. Kesimpulannya, penemuan medan elektrik yang dihasilkan di Malaysia didapati berbeza dalam banyak cara yang menambah pengetahuan baru mengenai penemuan yang dinyatakan sebelum ini. Ini penting kerana jenis aktiviti kilat menjejaskan cara di mana sistem-sistem perlindungan dibuat.

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I certify that an Examination Committee has met on date of viva voce to conduct the final examination of Muhammad Noh Bin Hamzah on his thesis entitled "Distinct Characteristics of Cloud-to-Ground Lightning Electric Fields Generated in Malaysia" in accordance with the Universities and University College Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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Declaration by Graduate Student

I hereby confirm that:

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Declaration by Members of Supervisor Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

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LIST OF ABBREVIATIONS

AM	Arithmetic Mean
BIL	Breakdown, Intermediete and Leader
BL	Breakdown and Leader
BS	British Standard
CA	Cloud-to-Air
CC	Cloud-to-Cloud
CELP	Centre for Electromagnetic and Lightning Protection Research
CG	Cloud-to-Ground
CID	Compact Intracloud Discharge
CL	Chaotic Leader
CPT	Chaotic Pulse Trains
CPV	Concentrating Photovoltaics
DSL	Dart Stepped Leader
ECMWF	European Centre for Medium-Range Weather Forecasts
FALLS	Fault Analysis and Lightning Location System
GC	Ground-to-Cloud
GM	Geometric Mean
IEC	International Electrotechnical Commission
KSC	Kennedy Space Center
NASA	National Aeronautics and Space Administration
NBE	Narrow Bipolar Event
NBP	Narrow Bipolar Pulse
NBP	Narrow Bipolar Pulses
NNBP	Narrow Negative Bipolar Pulse
NPBP	Narrow Positive Bipolar Pulse
PB	Pulse Burst
PBP	Preliminary Breakdown Pulses

RS	Return Stroke
SL	Stepped Leader
SS	Subsequent Strokes
TNB	Tenaga Nasional Berhad
TNBR	Tenaga Nasional Berhad Research
UPM	Universiti Putra Malaysia
VHF	Very High Frequency

LIST OF NOTATIONS

ΔT_1	10% to 90% Risetime
ΔT_2	0% to 100% Risetime
ΔT_{ZC}	Zero Crossing Time
C	Attachment Circuit Capacitor
C_b	Buffer Capacitor
C_c	Coaxial Cable Capacitance
C_g	Parallel Plate Antenna Capacitance
CPT-a	Chaotic Pulse Trains that occurs after last Return Stroke
CPT-b	Chaotic Pulse Trains that occurs before a First Return Stroke
CPT-c	Chaotic Pulse Trains that occurs before a Succeeding Return Stroke
CPT-i	Chaotic Pulse Trains that occurs Between Return Strokes
C_v	Variable Tail Capacitor
D	Distance of Other Peaks
EN	European Standard
E_p	Zero to Peak Risetime
F	Slow Front
L	Leader Pulses
LH0033	Buffer Amplifier
M_{AVG}	Average Multiplicity
N	Total Number of Negative Cloud-to-Ground Flash
PBP-RS	Preliminary Breakdown Pulse to Return Stroke
R	Decay Time Constant Resistor
r	Distance in which a Cloud-to-Ground Flash is Terminated
R	Fast Transition
R_0	Tail Resistor
R_1	Entrance Resistor

T_1	Zero Crossing Duration Definition
T_{CPT}	Chaotic Pulse Train Duration
$T_{CPT\text{-}PBP}$	Chaotic Pulse Train to Preliminary Breakdown Pulse Duration
$T_{CPT\text{-}RS}$	Chaotic Pulse Train to Return Stroke Duration
TEK	Tektronix File
T_{II}	Interstroke Interval
T_{PBP}	Preliminary Breakdown Pulse Duration
$T_{PBP\text{-}CPT}$	Preliminary Breakdown Pulse to Chaotic Pulse Train Duration
$T_{PBP\text{-}RS}$	Preliminary Breakdown Pulse to Return Stroke Duration
$T_{p\text{-}ri}$	Preliminary Breakdown Pulse to Return Stroke Time
$T_{RS\text{-}CPT}$	Return Stroke to Chaotic Pulse Train Duration
T_z	Zero Crossing Time
T_{ZC}	Zero Crossing Duration
τ_d	Decay Time Constant

CHAPTER 1

INTRODUCTION

1.1 Background

Lightning phenomenon has been studied for decades with Simpson and Scrase [1] and Simpson and Robinson [2] being some of the pioneers. Physical processes and activities that happen within the clouds initiates lightning flashes from one point to another when potential difference between opposite charges are significantly large. The transfer of charges can occur to the cloud itself, air, another cloud-or ground [3]. Thus, there are only 4 possible areas in which a flash can happen. In the context of cloud-to-ground (CG) lightning, the electric fields that are produced by charge build-ups in the cloud and on the ground results in an electrical breakdown which initiates a CG flash [4].

The types of thunderstorms can be generalized as shown in Figure 1.1. The positive and negative charges that are seen in the figure represent the tripolar electrostatic structure for the thunderclouds with a group of positive charges located in the uppermost part, a group of negative charges located in the middle part and a smaller group of positive charges located in the lower part of the three types of thunderclouds. This allows the thunderstorms to be divided into intra cloud (inside the cloud), CG and air discharge or cloud-to-air (CA) types of lightning flashes depending on the conditions in the cloud as can be seen in the figure. It should be noted that from the figure, there is no charge situated on the ground which plays a significant role in the type of flashes that are developed. There are more types of lightning discharges to be explained in the next section.

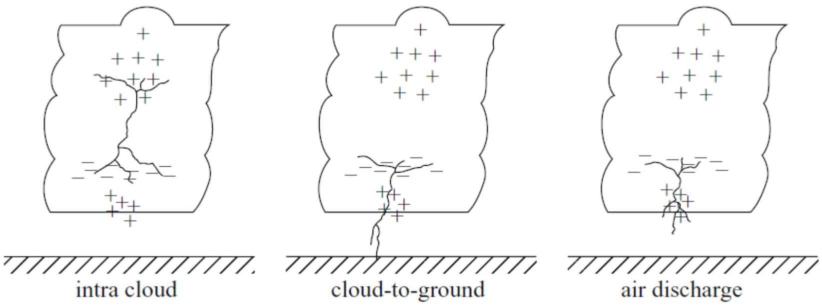

Figure 1.1. The Most Common Types of Lightning [3]

Details on the charges in the clouds and types of flashes can be seen as in Figure 1.2. In this figure, unlike the previous one, there is an involvement of positive and negative charges on the ground which can produce two types of CG lightning. They are the positive and negative CG flashes. Positive ground flash is defined when positive charges are being lowered to the ground while negative ground flash is defined when negative charges are being lowered to the ground by the cloud [5] Inter-cloud (between clouds) or cloud-to-cloud (CC) lightning is also introduced in Figure 1.2 in contrast to intra cloud lightning from Figure 1.1.

Another type of lightning which is quite unusual, rare and commonly associated with tall towers is the ground-to-cloud (GC) lightning or upward lightning [6, 7]. Air discharge is shown to discharge in a different way in the figure which depicts the idea of upward lightning that discharges from a low to a higher end. The various types of lightning give a broader view of what lightning can do and shows that there is still much to learn from the natural phenomena.

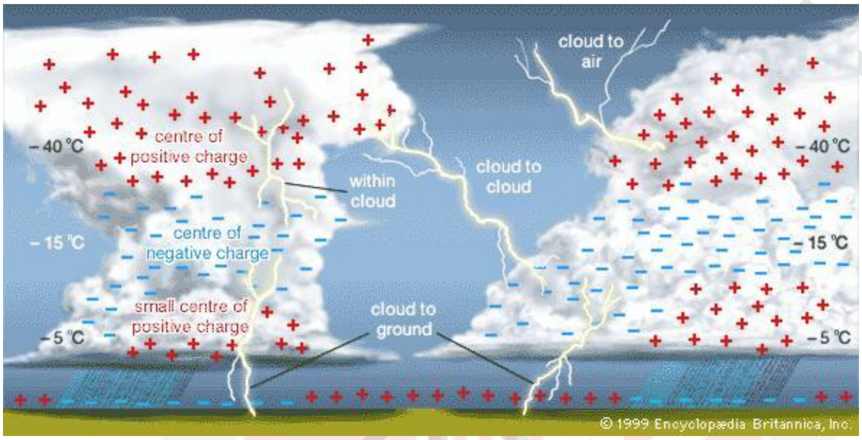

Figure 1.2. Types of Lightning [8]

Despite electrical systems, appliances and devices can be found almost everywhere around the world where energy is; they are vulnerable to the lightning risk. The risk involves flashes that occur from both cloud, and cloud-to-ground. Although cloud flashes can have a significant impact to systems such as having an effect towards aircrafts during its flight [9], this thesis focuses on flashes that discharge from cloud to ground. This is because CG lightning are affecting the human society in many ways and almost all of infrastructure of the human needs is stationed at the ground level [10]. Some of them are especially in causing damage from something as small as a sensitive electronic circuit to death of human lives [11, 12]. Forest fires are also caused by lightning that causes serious damage and must be dealt with quickly [13]. At sea levels, lightning can also impose threats such as interfering with the system of naval crafts [14]. On the contrary, new findings has proven that lightning can be put to use by harvesting energy from it that can be a new source of renewable energy [15]. Thus, it is clear and significant that the study of CG lightning is crucial for the safety and betterment of the lives of the society at whole. More significant factors of the importance this study will be seen in the next and latter sections.

The main concern of threat from CG lightning is towards human beings, animals and electrical systems. Being indoors does not necessarily mean the person is safe from being involved in a lightning accident; it only reduces the damage or probability. About

51% of lightning accidents happen indoors in the United Kingdom [16]. Figure 1.3 shows lightning injuries and deaths in Malaysia from different activities of occurrences [17]. Taking shelter from rain and lightning is on top of the list and this evidently shows that there is lack of knowledge and awareness of taking actions against rain and lightning from the majority of the community members. Animals have also been reported to be killed as a result of step voltages from lightning [18]. As for electrical system, electric field coupling is one of the ways lightning can damage electronic equipment [19]. As a result, induced voltage and currents are introduced into the system and can cause disruptions and damages.

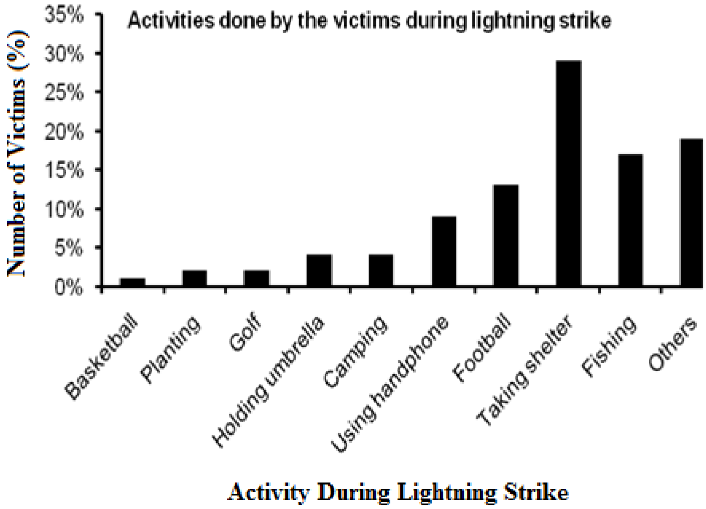

Figure 1.3. Statistics of Activities Done by Victims and Their Respective Numbers [17]

Inherently, there is no way that human beings can control the nature of lightning because it is a natural phenomenon. In Malaysia, CG flashes happen about 25% of the times compared to the other types of flashes [20]. The CG flashes can further be categorized into positive and negative lightning with positive lightning being not as frequent as the latter [21]. Nevertheless, positive lightning is more dangerous in nature and poses a larger threat compared to negative lightning [22]. Lightning is seemingly proving itself as a serious threat by the day. If the issue of lightning causing damage and disruptions is not addressed soon enough, more damage will be done in time.

Lightning hazard warnings are developed by electromagnetic field measurements as a means of protection against lightning using the motion of charges that travels within the proximity of the atmosphere when there is a lightning discharge. One of the fields that are being propagated is the electrostatic field component other than the induction or radiation field of the lightning discharge [23]. This gives an example of a kind of that serves as a basis for protection systems that is essential to warn against incoming lightning in close proximity of the sensitive electrical device or appliance. Interactions between lightning and the power system and devices will happen in areas that have a high density of lightning. Warning of incoming lightning can now be done before an actual thunderstorm by acknowledging the electric field at ground level. However, of course, there are many other methods to identify and minimize the lightning damage. Thus, it is important to study the characteristics of lightning to develop and derive standards for lightning protection systems accordingly from the measurements that have been taken.

Nowadays, only the vertical components of the electric field of the flashes are the point of interest of most studies due to its dominance over its horizontal counterpart. This is due to its contaminating effect from the vertical electric field which is significantly higher in magnitude making the horizontal counterpart difficult to measure [24]. Measured vertical lightning electric field shows that a typical CG lightning would normally contain preliminary breakdown pulses (PBPs), stepped leaders (SLs), dart stepped leaders (DSLs), negative and positive return strokes (RSs), subsequent strokes (SSs) and at times, chaotic pulse trains (CPTs) before it is fully neutralized [25-28]. Other kinds of lightning activity that are those of cloud lightning that is not the main focus of this thesis study but will be discussed to a certain extent due to their importance in classifying the types of flash. The trend is the similar to other regions over the world except in a few details that may vary.

Thunderstorms that happen due to the frequent rainfall in Malaysia make the study of the lightning generated electric fields essential and necessary. Malaysia is positioned along the equatorial line in the world making it a country that is high in terms of lightning activity and thunderstorms [29]. The information obtained by the Malaysian Meteorological Department tells that the rainfall and thunderstorm in Malaysia, particularly in the Selangor area is frequent seasonally every year [30]. Thus, the lightning flash that occurs during thunderstorms gives the opportunity to measure lightning electric fields as it is almost impossible to ignore the study in the region. With this, more data can be collected to improve the knowledge of lightning in Malaysia.

Obtaining information of rain forecast from outside of the country can help to predict rain and thunderstorm activity. However, relying on the local forecasts only may prove to be insufficient due to constraints that may exist in their system. Malaysian Meteorological Department has acquired weather outlooks from the European Center for Medium-Range Weather Forecasts (ECMWF) which is an independent organization body that does forecasts for countries around the world to obtain forecasts of seasonal weathers annually as an external source of weather information [31]. Although it is only a forecast, the model can give a good anticipation on when the rainfall and thunderstorm will occur for preparations in advance to do the measurements of the experiment. An example of a forecast done and used in this study can be seen in Figure 1.5. As can be seen in the figure, Malaysia has a good above average rainfall during November 2012, December 2012 and January of 2013 where ECMWF forecast is used for the 2012 and 2013 years. The forecast used for this study only uses some months from the 2013 and 2014 years.

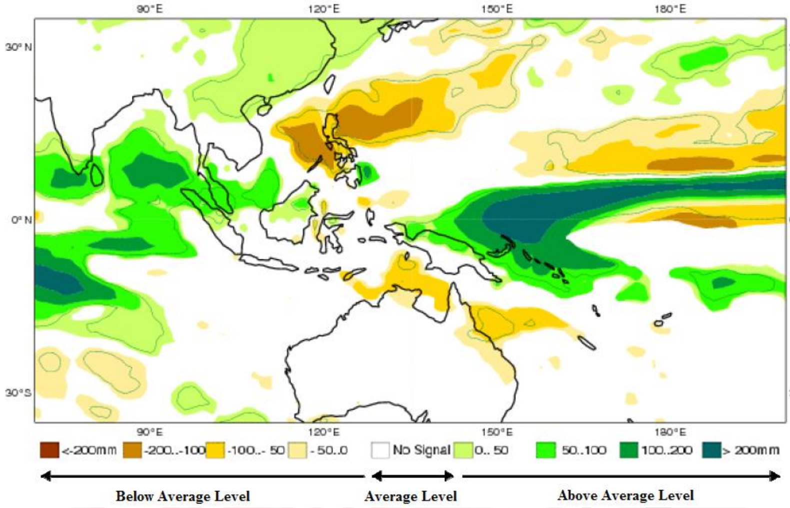

Figure 1.4. ECMWF Forecast for November-December 2012-January 2013 [32]

1.2 Problem Statement

In temperate regions such as Denmark, Sweden and Finland and sub-tropic regions such as Darwin, Florida and Oklahoma lightning vertical electric field are studied extensively. However, analysis of such lightning features in the tropics is scarce. The only countries with such studies are Sri Lanka and Malaysia. The studies done in the two countries are not as comprehensive as what is done in temperate regions resulting in a lack of knowledge in this field. This is a drawback in the development of models for engineering applications and understanding physics of lightning. Few of the outstanding gaps in knowledge with respect to tropical lightning are:

1) Detailed analysis of PBP and their temporal position.
2) Some unique and unusual features of negative and positive RS.
3) Temporal position (within the entire lightning flash) and characteristics of CPT.

The study of lightning generated is needed in Malaysia since there is frequent lightning activity present in the country. Studies in areas or states that are reasonably high in frequency of lightning events should be encouraged and conducted. Most of the studies are done on the analysis and statistics of the occurrences of PBPs and RSs with the parameters that are associated to those lightning activities. More studies are also needed for positive lightning and chaotic pulse trains and parameters that are acquainted to those studies. This is due to the fact that they are rare in nature and little is known of them so far. It is important to have an adequate knowledge of the lightning parameters in broader terms to have a clearer understanding of lightning physics in order to develop lightning protection systems.

1.3 Aim and Objectives

The main aim for this study is to conduct an in depth analysis of the measured electric fields obtained at the experimental site in Malaysia. PBPs, RSs and CPTs of flashes will be the main focus of the analysis.

A detailed explanation of the objectives of this study is as follows:

1) Redevelopment of a comprehensive measuring system to capture fast field vertical electric field due to lightning.
2) Record and analysis of PBP, RS (negative and positive) and CPT of CG lightning for investigating their unique characteristics.
3) Comparison of features of Malaysian CG lightning with that in other regions.

1.4 Scope and Limitations

The work process begins with studying the related literature. This includes the cloud and ground flashes of almost every type of lightning activity such as the PBPs, SLs, DSLs, RSs, CPTs and a small number of cloud flashes like PBs and NBPs. Literature regarding the time of rain is also studied mainly obtained from the meteorological department for weather forecasts. After studying the literatures, the types of findings are listed out. The types of study and literature are also influenced by the measurement results as the study progresses. More research is needed for preliminary breakdown pulses, negative lightning, positive lightning and chaotic pulse trains especially in Malaysia as a tropical region since they scarce in number.

The next step is to develop the experimental setup at the site. Maintenance of the setup is made to ensure the setup is working and accurate. It is crucial to make sure the setup is working properly. A wrong setup may lead to incorrect and undesirable results. It is done from time to time before any real measurements are done. A few test runs of the measurements are completed to ensure the desired data can be obtained and confirm the reliability of the setup. Measurements of lightning generated electric fields are recorded every time a forecasted rain with thunderstorm from the meteorological department of Malaysia is taken place. Data are then collected, distinguished, characterized, analysed and compared to previous studies to complete the objective of the study. An estimated time to complete the work process is about 5 to 10 months if everything goes well and as planned. Finally, the lightning location data from TNBR using their FALLS are also acquired to complete the study in order to determine whether a CG flash is from the radiation field or otherwise.

1.5 Thesis Outline

The outlines of the thesis can be seen as follows.

Chapter 1 introduces the study by explaining the background, problem statement, aim, objectives and outlines of the thesis study. This chapter provides a clear view of the study and its scope.

Chapter 2 defines and analyse the literature on lightning parameters. Studies regarding lightning activities of past researchers are mentioned and presented in this chapter. Some of the cloud flashes are brought up but most of the literature contains the explanations of CG flashes. PBPs, RSs and CPTs are the main focus of the study along with the explanation of their occurrences in CG flashes and analysis.

Chapter 3 explains the methodology of the whole study process. From the beginning of the development of the experimental setup to the measurements and the approaches to analyse the data, every step is carefully examined in detail.

Chapter 4 presents the results and findings of the measurements at the site. Detailed analysis and explanations on the PBPs, RSs and CPTs are discussed in this section.

Chapter 5 concludes the thesis with limitations, constraints, recommendations for improvements and possibility of future work. The contribution of the thesis to the scientific community is also highlighted in this chapter.

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