TIME DIFFERENCE OF ARRIVAL-BASED THREE-STATION LIGHTNING LOCATING SYSTEM IN MALAYSIA

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“To my beloved parents and wife, for their encouragement and support”

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ABSTRACT

Lightning is an electrical discharge that happens during thunderstorms. The discharge type can be either within cloud (IC), cloud-to-cloud, or cloud-to-ground (CG). The characterisation of a discharge activity based on the analysis of the measured electric field is widely studied in various geographical conditions. The technique of locating a CG flash is also widely researched. However, little is known on the discharge characteristics in equatorial and tropical regions, such as those associated with preliminary breakdown pulses (PBPs) and return strokes (RSs). Similarly, improvements can still be made on Lightning Locating Systems (LLSs), especially those using the time of arrival (TOA) technique. In particular, the operation of a three-station LLS to correctly locate a CG flash is very much desired to be proven. This work aims to obtain and analyse the lightning discharge characteristics in Malaysia. The work also proposes a new TOA based technique to correctly locate a CG flash using only three measuring stations. Measurements had been made in southern Malaysia using a purposely designed lightning detection system comprising a broadband antenna. A three-station TOA based LLS had also been implemented. The new TOA based technique was developed using the three-station LLS modelling in Matlab and artificial neural network (ANN). A discrete wavelet transform based technique was successfully developed to classify the discharge type. Self-Organizing Maps and Levenberg–Marquardt algorithms can identify the correct strike position with 2.5% error. The trained ANN engine was used to determine flash locations in a 400 km^2 region. The three-station LLS gives superior results in terms of detection accuracy and efficiency when compared with those measured by Malaysian Meteorological Department.

ABSTRAK

Kilat adalah discas elektrik yang berlaku semasa ribut petir. Discas berlaku di dalam awan (IC), awan ke awan, atau awan ke bumi (CG). Pencirian aktiviti discas berdasarkan analisis medan elektrik yang diukur telah dikaji dengan meluas dalam pelbagai keadaan geografi. Teknik penentuan lokasi kilat CG juga dikaji dengan meluas. Walau bagaimanapun, sedikit yang diketahui berkaitan pencirian discas di kawasan Khatulistiwa dan tropika, seperti yang berkaitan dengan denyutan pecahtebat awal (PBPs) dan panahan balik (RSs). Penambahbaikan juga masih boleh dibuat ke atas Sistem Lokasi Kilat (LLSs), terutamanya yang menggunakan teknik masa ketibaan (TOA). Khususnya, operasi LLS tiga-stesen untuk penentuan lokasi kilat CG secara tepat amat dikehendaki untuk dibuktikan. Kajian ini bertujuan untuk mendapat dan menganalisis ciri discas kilat di Malaysia. Kajian ini juga mencadangkan satu teknik baru berasaskan TOA untuk menentukan lokasi kilat CG secara dengan hanya menggunakan tiga stesen pengukur. Pengukuran telah dibuat di selatan Malaysia menggunakan sistem pengesanan kilat yang telah direka menggunakan antena jalur lebar. LLS tiga-stesen berasaskan TOA telah dilaksanakan. Teknik baru berasaskan TOA telah dibangunkan menggunakan pemodelan LLS tiga-stesen menggunakan Matlab dan rangkaian neural buatan (ANN). Satu teknik berasaskan jelmaan *wavelet* diskret untuk mengklasifikasikan jenis discas telah berjaya dibangunkan. Algoritma-algoritma *Self-Organizing Maps* and Levenberg–Marquardt boleh mengenal pasti kedudukan panahan dengan ralat 2.5%. Enjin ANN terlatih telah digunakan untuk menentukan lokasi kilat di sesebuah kawasan seluas 400 km^2. LLS tiga-stesen memberikan keputusan yang lebih baik dari segi ketepatan dan kecekapan pengesanan berbanding data dari Jabatan Meteorologi Malaysia.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AI	-	Artificial Intelligence
ANN	-	Artificial Neural Network
CG	-	Cloud-to-Ground
CID	-	Compact intracloud discharges
DWT	-	Discrete Wavelet Transform
FFNNs	-	Feed-Forward Neural Networks
GPS	-	Global positioning system
IC	-	Inter Cloud
IMPACT	-	Improved Accuracy through Combined Technology
LDN	-	Lightning Detection Network
LLS	-	Lightning Location System
LMA	-	Lightning Mapping Array
MDF	-	Magnetic Direction Finding
MMD	-	Malaysian Meteorological Department
MSD	-	Multiresolusion Signal Decomposition
NBP	-	Narrow bipolar pulses
PBP	-	Preliminary Breakdown Pulse
SAFIR	-	Systeme d'alerte Foundre par Interferometrie
SOM	-	Self-organizing maps
TDOA	-	Time difference of arrival
TNBR	-	Tenaga Nasional Berhad Research
TOA	-	Time of Arrival
UTM	-	Universiti Teknologi Malaysia
UTM (LLS)	-	Lightning location system developed in UTM
VHF	-	Very High Frequency
VLF	-	Very Low Frequency
WWLLN	-	World Wide Lightning Location Network

LIST OF SYMBOLS

°C	-	Degree Celsius
Ω	-	Ohm
E	-	Electric field intensity
ε	-	Relative permittivity
ε_o	-	Dielectric permittivity
I	-	Current
C	-	Capacitor
e_J	-	Instantaneous error
Q	-	Charge
d	-	Distance
f	-	Frequency
V	-	Voltage
f_c	-	Cut-off frequency
V*s*	-	Supply voltage
t	-	Time
Lat	-	Latitude
Lon	-	Longitude
J	-	Number of decomposition levels
N	-	Number of samples
a_k	-	Spectrum coefficients
m	-	Slope

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Research Background

Lightning can cause harm to both human lives and properties. A readily available system for detection and warning of an incoming lightning storm is therefore very useful. Public individuals scarcely own or install the lightning detection systems. It is a major disadvantage if the public is unable to receive the warning message at the very earliest time when a lightning strike is approaching. It may expose the people near the lighting strike location to danger, especially for those undergoing an outdoor activity. Therefore, a lightning detector which is able to detect the lightning strike distance will be the useful for the public citizens in protecting themselves from lightning strikes. In order to map the precise location of a lightning strike, both distance and direction are important. This data is useful for insurance companies and for protection purposes.

Previous work on the lightning locating system (LLS) includes the studies using various detection techniques such as time difference of arrival (TDOA) [1], magnetic direction finding (MDF) [2, 3], and interferometry [4]. However, these techniques have their own advantages and disadvantages. Among the problem encountered in these techniques are 1. Low accuracy (All); 2. High cost (All); 3. Not exactly real time (TDOA, DF); and 4. Time synchronization problem (TDOA). One method of increasing the accuracy is by using VHF sensors for small coverage area.

Previous work [5] show that accuracy can be increased by more than 90% in the small scale area.

Even though there is a lot of research done on the LLS, still many improvements can be made regarding the time synchronization, time difference measurements, detection accuracy, and detection efficiency. This work aims to provide a localized LLS based on the TDOA method with the utilization of high resolution time synchronization and time difference measurements.

Discrimination between a different types of lightning flashes such as cloud activity and cloud-to-ground (CG) flashes has long been recognized as a challenge in lightning research. Some well-known models such as BIL and BL are used to identify the CG flashes. Several parameters such as the rise time and gradient of pulses can also be used to differentiate cloud activities and CG lightning flashes. In short, a precise analysis of the signals is required to differentiate the various type of discharges. This analysis is usually carried out manually [6].

A reliable lightning location system can be considered as invaluable. It helps to save lives and reduce the risk of losing huge capital when arranging operations such as space shuttle launches and airport services. The technology also helps in effective decision making, for example, the deployment of emergency crews for quick recovery of essential electrical or electronic systems. It also serves as a warning system for future or probable lightning occurrence so that people could plan their outdoor activities accordingly and ultimately saves lives.

1.2 Problem Statement

Lately, there have been a lot of interest on lightning related research. In particular, studies have been done to better characterize lightning phenomenon including those within the cloud prior to the cloud-to-ground flash. Among the highly researched topics are related to Preliminary Breakdown Pulses (PBPs), and processes in Cloud-to-Ground (CG) flashes including the return strokes (RS). Since lightning is much related to statistical data, lack of such data hinders the research progress. Comparative studies on lightning discharge processes in different meteorological conditions can contribute to better understanding of the lightning breakdown process. However, there are only a few measurements done in equatorial regions. The characterization of lightning discharges in equatorial regions is therefore needed to be studied in detail.

The identification of a lightning discharge type based on the electric field waveform analysis can be manually achieved using human eye according to some well-known parameters such as the gradient of fluctuation and the temporal analysis. Even though an automated identification of the lightning discharge type is difficult due to the complexity of the electric field waveform, this capability should be available in a modern LLS. Nevertheless, most of currently installed LLSs throughout the world are unable to provide an automated method to differentiate between different types of lightning discharges such as within cloud, cloud-to-cloud, and cloud-to-ground. The development of a suitable algorithm to successfully differentiate various types of lightning discharges is highly desirable.

Lightning detection studies had been previously carried out by many researchers [7-10]. These include direction finding (DF), time difference of arrival (TDOA) techniques, a combination of these two, and interferometry methods. All techniques need a number of sensors within a network to get reliable data on the location of a lightning flash. The TDOA method uses the small differences in the arrival times of the radio wave at different stations to determine the optimum distance to the flash from a network of synchronized stations. However, these techniques have their own advantages and disadvantages. Some of the usual disadvantages faced by these techniques are high cost, low detection accuracy, and low detection efficiency due to their relatively large coverage area [11, 12]. Improvements can still be made on lightning locating systems (LLSs), especially those using the time of arrival (TDOA) technique. It is well known that the lightning location system using TDOA method needs at least four measuring stations. The solving of the TDOA algorithm using a lesser number of measuring stations will definitely results in two or more solutions for a given strike location. The concept of using only three stations in an LLS and yet it can correctly locate a CG flash is very much desired to be proven.

1.3 Research Objectives

The objectives of this study are listed as follows:

(i) To develop, design, and construct a prototype of an on-line lightning locating and monitoring system consisting of three receiver sensors, a central device, and processing programs.

(ii) To prepare statistical information on BIL model of CG lightning discharge in Malaysia based on the measured electric field waveforms.

(iii) To develop a suitable algorithm to successfully differentiate cloud activity and cloud to ground of lightning discharges.

(iv) To correctly locate a cloud-to-ground flash in a three-station TDOA-based LLS with the help of Matlab modelling and artificial neural network training and assess the performance of the developed three-station TDOA-based LLS.

1.4 Research Scope

Several scopes are listed to ensure the research is conducted within its intended boundary. These are:

(i) Only the vertical component of the lightning electric field was measured. This is considered acceptable since the analysis of the vertical component of the electric field is sufficient to represent the lightning discharge behaviour.

(ii) Identifying the correct position of the lightning ground flash will be done in the neural network ToolBox of Matlab. Therefore, developing and constructing a new neural network algorithm is not part of this research study.

(iii) Only one configuration of the three-measuring station LLS was installed and tested. The measurements are limited to the ones made in 400 km^2 area around the campus of Universiti Teknologi Malaysia, Johor Bahru, in August 2014. Comparisons with other LLS data are also limited to this specific coverage area only.

(iv) The lightning discharge characterisations are based on 290 flashes measured using one measuring station located at the Observatory, Universiti Teknologi Malaysia. The measurements were made within the period between December 2012 and May 2013. The measured data is deemed sufficient to represent the discharge behaviour in an equatorial or tropical region.

1.5 Contributions of Research

The contributions of this thesis are outlined as below:

(i) Comparative studies on lightning discharge processes in different meteorological conditions can contribute to better understanding of the lightning breakdown process. However, there are only a few measurements done in equatorial regions. One of the contribution of this study is to prepare statistical information of lightning electric fields measured in Malaysia. The measurement setup was successfully designed, constructed, and installed at the UTM's Observatory, and measurements were made within several months in 2012 and 2013. Analyses on 290 captured lightning electric field waveforms led to first, the identification of main parts within the waveform such as the Cloud activity, Isolated, and Cloud-to-Ground (CG) discharge, and second, the key characteristics of each part, for example, the Preliminary Breakdown Pulses (PBPs). There are some similarities and differences observed between this study and other studies. Possible causes of any difference between this study and other studies, may be due to the different geographical region, latitude, and meteorological conditions.

(ii) An on-line prototype lightning location system which consists of three measuring station parallel plate antenna sensors, has been designed, constructed, installed, and tested. By applying the Time of Arrival (TDOA) method, the lightning ground flash coordinate is determined using the Matlab and LabView software. The software is to capture and analyze the recorded signal and map the coordinates of lightning ground flashes. Linear simulation and mathematical analysis of the TDOA method is necessary in order to evaluate error of system. A total of 556 ground flashes were successfully detected and mapped across the south region of Malaysia during six different measuring days from August 2014. The current intensity value of all captured lightning ground flash is also estimated.

(iii) It is well known that the lightning location system using TDOA method needs at least four measuring stations to avoid the ambiguous location of lightning ground flash. In this work, it was shown that even using three measuring stations, a correct location of the strike can still be achieved. A new approach to identify the correct position of a lightning strike using a combination of artificial neural network algorithms, namely Levenberg–Marquardt and Self-Organizing Map, is successfully developed and tested. It was demonstrated that the ANN engine can correctly identify the true coordinate of lightning ground flash with an acceptable error of 2.5%. The developed codes and weight matrices for all trained networks were successfully obtained and can be used as required.

(iv) An automated discrimination between a cloud activity signal and a cloud to ground signal has long been recognized as a challenge in the lightning research area. A Multi-resolution Signal Decomposition (MSD) technique which utilises the Discrete Wavelet Transform (DWT) was successfully identified and developed to classify different types of lightning electric field. A comparison between 50 cloud flashes and 50 CG flashes illustrates that there is no overlap in the first level of energy for all flash samples. An energy value of 6.27 was chosen as the boundary level to distinguish between a cloud activity and a CG flash.

(v) In evaluating a lightning location system, both the detection accuracy and detection efficiency are needed to assess the system performance. Lightning data had been gathered for a certain period of time using the three-station lightning locating system developed in this study. Comparisons with the data provided by Tenaga Nasional Berhad Reseach (TNBR) and Malaysian Meteorological Department (MMD) show that the three-station lightning locating system performs better in terms of detection efficiency (number of cloud-ground flashes only) and detection accuracy (coordinate location). The comparison statistics clearly show that more than 70 percent of data were well matched to the MMD data. The Average of time difference between MMD and UTM (LLS) was found to be 22.58568 second. The arithmetic mean location error was about 296.481111 m.

1.6 Thesis Outline

Chapter 1 provides the topic background, reasons to carry out this thesis, goals to meet to accomplish this work, objectives, scope, and achievements of the research.

Chapter 2 covers a comprehensive review in the lightning research area. Those are the mechanism of lightning, lightning types and steps, method of lightning detection, application of GPS in lightning location system, application of artificial intelligent in the lightning location system and wavelet transform technique. Most of the published works deliberated on the accuracy and efficiency of the lightning detection system. However, it is found that each method may have one or several shortages to provide a high accuracy and best efficiency.

Chapter 3 presents the hardware installation and analysis methods. In this chapter the construction of the circuit board and the hardware implementation is described. To overcome on the limitation of the TDOA method by three measuring stations Levenberg–Marquardt and the Self-Organizing Map algorithms in the artificial neural network is conducted. Classification of lightning electric field types is considered using multi-resolution signal decomposition and a new algorithm to identify cloud to ground signals is proposed.

Chapter 4 discusses on the results, which are obtained from the practical measurement performed in 3 different periods during 2012 to 2014. Characteristic of lightning electric fields before for the duration prior to, during, and after the return stroke in tropical region is presented and characteristic of the lightning in tropical region will be compared with other geographical region and this knowledge of lightning will greatly advance our knowledge on lightning with respect to the spatial and temporal occurrence of lightning all over the world. In the next part of this chapter lightning ground flash happened on six different days in August 2014 is localized, and the result of this study is compared with well-known currently installed lightning data provider.

Chapter 5 presents the conclusions and discussions of this study. Future work and recommendations are also highlighted in this chapter.

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