Faculty of Electronics and Computer Engineering

EVALUATION AND OPTIMIZATION OF WAVELET TECHNIQUE TO ENHANCE THE MAPPING ACCURACY OF LIGHTNING VHF INTERFEROMETRY

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EVALUATION AND OPTIMIZATION OF WAVELET TECHNIQUE TO ENHANCE THE MAPPING ACCURACY OF LIGHTNING VHF INTERFEROMETRY

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DECLARATION

I declare that this thesis entitled “Evaluation and Optimization of Wavelet Technique to Enhance the Mapping Accuracy of Lightning VHF Interferometry” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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Date : 27 June 2022

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Doctor of Philosophy.

Signature : ……...

Supervisor Name : Dr. Mohd Riduan Ahmad

Date : 27 June 2022

DEDICATION

There are several people without whom and their fully support and encouragement this thesis may not have been written, and to whom I am greatly indebted.

To my beloved father Mohammed Qaid Al-ammari for his help and unlimited prayers, and my mother Fandah Saleh Muthanna who has been a source of encouragement and inspiration to me throughout my PhD journey.

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ABSTRACT

Despite the significant progress in the understanding of the phenomenon of lightning and the physics behind it, locating and mapping its occurrence remain a challenge. Such localization and mapping of very high frequency (VHF) lightning radiation sources provide a foundation for the subsequent research on predicting lightning, saving lives, and protecting valuable assets. A major technical challenge in attempting to map the sources of lightning is mapping accuracy. Several methods have been proposed for estimating the real pattern of the temporal location and spatial map of the lightning strikes. However, due to the complexity of lightning signals and the noise accompanying its recording, providing accurate lightning maps estimation remains a challenging task. To advance the lightning mapping it is vital to improve how lightning signals are pre-processed and how noise is filtered. Most existing studies of lightning mapping make use of the VHF interferometer (ITF) alongside cross-correlation in time and frequency domain and phase difference of arrival techniques. These methods involve selecting a set of parameters which usually fail to accommodate all types of lightning flashes, discarding information that could be beneficial for further improvement of lightning mapping accuracy. In this thesis, a wavelet-based cross-correlation (CCWD) is proposed for a reliable lightning mapping estimation through means of signal enhancement and noise reduction, providing a better time- frequency resolution. Interpolation techniques were introduced to smoothen the correlation peaks for more accurate lightning localization. To confirm the effectiveness of the proposed method, a simulation of lightning signals was created, and the mapping results were verified. Moreover, a comparative study to investigate the effectiveness of different processing techniques was carried out. The benchmark environment involved the use of different filtering and cross-correlation techniques, introducing new processing methods such as Kalman filter and wavelet-based cross-correlation. In addition, a particle swarm optimization technique is used to optimize the trajectory of the CCWD-based lightning maps by finding the optimal sliding window of the cross-correlation. The CCWD-PSO technique was further enhanced through the introduction of a novel lightning event extraction method that enables faster processing of the lightning mapping. Six positive narrow bipolar events were analyzed, and the results indicate that a good estimation of the lightning radiation sources was achieved using wavelet de-noising and CCWD with a minimal error of 3.46°. The results were further improved with the use of CCWD-PSO technique with Euclidean distance of 0.6243 at 300 iterations. The investigations carried out in this study confirm that the ITF mapping system could effectively map the lightning VHF radiation source, which makes the combination of ITF and the CCWD a potential candidate for lightning mapping technology.

PENILAIAN DAN PENGOPTIMUMAN TEKNIK GELOMBANG KECIL UNTUK MENINGKATKAN KETEPATAN PEMETAAN INTERFERROMETRI KILAT VHF

ABSTRAK

Walaupun terdapat kemajuan yang signifikan dalam pemahaman fenomena kilat dan fizik yang mendasarinya, mencari dan memetakan kejadian tersebut masih mencabar. Penyetempatan dan pemetaan sumber radiasi kilat frekuensi sangat tinggi (VHF) menjadi asas kepada penyelidikan lanjut dalam meramal kilat, menyelamatkan nyawa, dan melindungi aset berharga. Cabaran teknikal utama dalam usaha memetakan sumber kilat ialah ketepatan pemetaan. Beberapa kaedah telah dicadangkan untuk menganggar pola sebenar lokasi temporal dan peta ruang pancaran kilat. Walau bagaimanapun, disebabkan kerumitan isyarat kilat dan bunyi yang dirakam serentak, menyediakan anggaran peta kilat yang tepat merupakan tugas yang mencabar. Untuk meningkatkan peta kilat, adalah amat penting untuk memperbaiki bagaimana isyarat kilat diproses dan bagaimana bunyi disaring. Sebilangan besar kajian mengenai pemetaan kilat menggunakan interferometer VHF (ITF) di samping korelasi silang dalam domain masa dan frekuensi dan perbezaan fasa teknik ketibaan. Kaedah ini melibatkan pemilihan sebuah set parameter yang biasanya gagal mengendalikan semua jenis pancaran kilat yang mengabaikan maklumat yang mungkin bermanfaat untuk peningkatan ketepatan pemetaan kilat. Dalam tesis ini, korelasi silang berdasarkan gelombang kecil (CCWD) dicadangkan bagi anggaran pemetaan kilat yang boleh dipercayai melalui peningkatan isyarat dan pengurangan bunyi yang memberikan resolusi frekuensi waktu yang lebih baik. Teknik interpolasi diperkenalkan bagi meratakan puncak korelasi untuk penyetempatan kilat yang lebih tepat. Bagi mengesahkan keberkesanan kaedah yang dicadangkan, simulasi isyarat kilat dicipta dan hasil pemetaan disahkan. Selain itu, kajian perbandingan untuk mengkaji keberkesanan teknik pemprosesan yang berbeza telah dijalankan. Persekitaran penanda aras melibatkan penggunaan teknik penyaringan dan korelasi silang yang berbeza memperkenalkan kaedah pemprosesan baru seperti saringan Kalman dan korelasi silang berasaskan gelombang kecil. Selain itu, teknik pengoptimuman kawanan partikel digunakan untuk mengoptimumkan trajektori peta kilat berasaskan CCWD dengan mendapatkan tetingkap slaid korelasi silang yang optimum. Teknik CCWD-PSO dipertingkatkan dengan pengenalan metode baharu pengekstrakan kejadian kilat yang memungkinkan pemprosesan pemetaan kilat lebih pantas. Enam peristiwa bipolar sempit positif dianalisis dan keputusan menunjukkan bahawa anggaran sumber radiasi kilat yang baik dicapai dengan menggunakan nyah bunyi gelombang kecil dan CCWD dengan ralat minimum 3.46°. Keputusan tersebut diperbaiki dengan penggunaan teknik CCWD-PSO dengan jarak Euclidean 0.6243 pada lelaran 300. Penyelidikan yang dilakukan dalam kajian ini mengesahkan bahawa sistem pemetaan ITF dapat memetakan sumber radiasi kilat VHF dengan berkesan yang menjadikan kombinasi ITF dan CCWD sebagai calon berpotensi teknologi pemetaan kilat.

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LIST OF SYMBOLS AND ABBREVIATIONS

1D	-	One Dimension
2D	-	Two Dimension
3D	-	Three Dimension
AI	-	Artificial Intelligence
ANN	-	Artificial Neural Network
AZ	-	Azimuth Angle
BPF	-	Band Pass Filter
KF	-	Kalman Filter
BW	-	Band-width
CC	-	Cross-Correlation
CG	-	Cloud-to-Ground
DC	-	Direction Correlation
DITF	-	Digital Interferometer
DOA	-	Direction of Arrival
EL	-	Elevation Angle
EM	-	Electromagnetic Radiations
FFT	-	Fast Fourier Transform
FFA	-	Firefly Algorithms
GCC	-	Generalized Cross-Correlation
GLIMs	-	Global Lightning and Sprite Measurements

GC/s	-	Giga-Samples Per Second
IC	-	Intra-Cloud flashes
DL	-	Dart Leader
ITF	-	Interferometer
LDAR	-	Lightning Detection and Ranging System
LF	-	Low Frequency
LLS	-	Lightning Localization System
LMA	-	Lightning Mapping Array
LMD	-	Lightning Mapping Detection
LNA	-	Low Noise Amplifire
MDF	-	Magnetic Direction Finding
MS/s	-	Mega Samples Per Second
NLDN	-	National Lightning Detection Network
LINET	-	Lightning Detection Network
USPLN	-	US Precision Lightning Network
ENTLN	-	Earth Networks Total Lightning Network
WWLLN	-	World Wide Lightning Location Network
GLD360	-	Global Lightning Dataset
PSO	-	Particle Swarm Optimization
SNR	-	Signal-to-Noise Ratio
TD	-	Time Difference
TDOA	-	Time Difference of Arrival
TOA	-	Times –of-Arrival
UHF	-	Ultra High Frequency
ULF	-	Upper High Frequency

VHF - Very High Frequency

VLF - Very Low Frequency

WD - Wavelet Domain

WT - Wavelet Transform

TDL - Triggered Dart Leader

TDCC - Time Domain Cross-Correlation

FTCC - Frequency Domain Cross-Correlation

WDCC - Wavelet Domain Cross-Correlation

SR - Sampling Rate

PSO - Particle Swarm Optimization

CCWD-PSO- Cross-correlation wavelet domain-based particle swarm optimization

FA - Fast Antenna

EM - Electromagnetic Waves

IIR - Infinite Impulse Response

A4 - Parallel plate antenna of size A4

A3 - Parallel plate antenna of size A3

ACO - Ant Colony Optimization

GA - Genetic Algorithm

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CHAPTER 1

INTRODUCTION

1.1 Background

Lightning is a natural phenomenon in which electrical discharges occur between two objects with different polarities. It may occur between clouds and the ground, between two clouds, or within a cloud. When discharges are generated, electromagnetic (EM) radiations over frequencies ranging from ultra-low frequency to ultra-high frequency, are produced (Cummins et al., 1998). Lightning discharges are mainly categorized into two types, namely, cloud-to-ground (CG) discharges, for example downward negative, upward negative, downward positive, and upward positive and in-cloud discharges (intra-cloud (IC), cloud to cloud (CC), and cloud-to-air) (Shao and Krehbiel, 1996; Rison et al., 1999; Thomas et al., 2001; Zhang et al., 2012; Sun et al., 2013). Although the physics behind lightning initiation remains unclear, many hypotheses have been proposed in the literature. Two candidate theories about lightning initiation have been considered, and they are hydrometeor-initiated positive streamers and cosmic ray-initiated runaway breakdown (Petersen et al., 2008). When the electric field between charges becomes sufficiently large, lightning is initiated. The massive amount of electromagnetism generated makes lightning a major cause of EM interference that can affect various electronic systems. Lightning is also one of the major causes of death in various countries around the world. Hence, different lightning mapping systems have been introduced long ago to protect humans and valuable assets. However, these old systems have problematic processing times because they are implemented offline (Manabu Akita1, 1955; Rison et al., 1999; Ushio et al., 2011; Stock et al., 2014; Zeng et al.,