EARTH MAGNETIC FIELD DATA ANALYSIS FOR EARTHQUAKE STUDY

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EARTH MAGNETIC FIELD DATA ANALYSIS FOR EARTHQUAKE STUDY

by

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LIST OF SYMBOLS

D_{AV}	Declination angle [deg]
$\frac{\delta D}{\delta t}$	Rate of Change of Geomagnetic Component- D [nT/s]
$\frac{\delta H}{\delta t}$	Rate of Change of Geomagnetic Component- H [nT/s]
$\frac{\delta Z}{\delta t}$	Rate of Change of Geomagnetic Component- Z [nT/s]
b	Baseline
D	Geomagnetic Eastward Component [nT]
F	Total Magnetic Field [nT]
H	Geomagnetic Northward Component [nT]
LT	Local Time
M	Richter Scale [Mw]
UTC	Coordinated Universal Time
X	Geographic Northward Component [nT]
Y	Geographic Eastward Component [nT]
Z	Vertical Down Component [nT]
δD	Variation of Geomagnetic Component- D [nT]
δH	Variation of Geomagnetic Component- H [nT]
δZ	Variation of Geomagnetic Component- Z [nT]

LIST OF ABBREVIATIONS

DST	Disturbance Storm Time
EEJ	Equatorial Electrojet
ICSWSE	International Centre for Space Weather Science and Education
INTERMAGNET	International Real-Time Magnetic Observatory Network
KP	Planetary K-index
MAG-9	MAGDAS-9 type magnetometer
MAG-II	MAGDAS-II type magnetometer
MAGDAS	Magnetic Data Acquisition System

ABSTRAK

Kedua-dua sistem INTERMAGNET dan MAGDAS adalah rangkaian magnetometer bumi yang telah dibangunkan untuk tujuan kajian cuaca angkasa lepas dan memantau variasi geomagnetik. MAGDAS-II magnetometer telah dipasang di Pulau Pinang untuk memantau variasi medan geomagnetik untuk kajian aktiviti seismik. Disebabkan stesen MAGDAS di Pulau Pinang baru dibina, sensitiviti magnetometer tersebut harus diuji dengan membandingkan datanya dengan data geomagnetik yang diperoleh daripada sistem INTERMAGNET. Stesen INTERMAGNET yang dipilih untuk kajian ini adalah daripada Dalat, Vietnam. Ini disebabkan kedua-dua stesen adalah berdekatan dengan garisan geomagnetik 0 deg. Variasi komponen geomagnetik H, D, dan Z yang diperoleh daripada kedua-dua stesen ini harus dianalisis untuk mengesahkan keberkesanan magnetometer MAGDAS yang baru dipasang. Sebenarnya, magnetometer biasa digunakan untuk memerhatikan perubahan dalam medan magnet Bumi sebelum berlakunya sesuatu aktiviti seismik. Hal ini disebabkan, sebelum berlakunya sesuatu aktiviti seismik seperti gempa bumi, lapisan litosfera akan mengalami tekanan yang dapat dirakam di stesen geomagnetik yang berdekatan. Oleh itu, kajian ini juga memfokuskan hubungan antara variasi geomagnetik dengan gempa bumi yang telah berlaku di Sumatera dari tahun 2015 hingga 2020. Variasi komponen geomagnetik H, D, dan Z harus dipantau sebulan sebelum gempa bumi untuk mengenal pasti hubungan antara mereka. Sebarang variasi anomali yang diperhatikan dalam medan geomagnetik dapat dijadikan sebagai amaran gempa bumi untuk mencegah pengorbanan nyawa dan kerosakan struktur.

EARTH MAGNETIC FIELD DATA ANALYSIS FOR EARTHQUAKE STUDY

ABSTRACT

Both International Real-Time Magnetic Observatory Network (INTERMAGNET) and Magnetic Data Acquisition System (MAGDAS) are ground-based magnetometer networks that have been developed to study the space weather. and monitor the geomagnetic variations. A MAGDAS-II type magnetometer was installed at Penang recently for seismic monitoring. Since the MAGDAS station is newly established, the sensitivity and reliability of the magnetometer had to be tested by comparing its data with geomagnetic data obtained from another well-established magnetometer system, INTERMAGNET. The INTERMAGNET station that was chosen for this study is Dalat, Vietnam. The variations of the geomagnetic components H, D, and Z obtained from both stations are analysed to verify the effectiveness of the newly installed MAGDAS magnetometer for seismic monitoring. Magnetometers used to observe the changes in Earth's magnetic field for earthquake study. The change in the Earth's magnetic field is caused by the increase in stress field within the lithospheric layers prior to an earthquake which can be recorded at geomagnetic stations of a specific distance. Therefore, this research also focused on examining the relationship between geomagnetic variations and earthquakes in Sumatra from 2015 to 2020. Hence, the behaviour of the geomagnetic components H, D, and Z before the earthquake must be monitored to identify a possible association between them. Any anomalous variation observed in the geomagnetic field can be used as a precursor for earthquakes to prevent casualties and damages.

ENDORSEMENT

I, (Sivanandini A/P Selvakone) hereby declare that I have checked and revised the whole draft of dissertation as required by my supervisor.

(Signature of Student)

Date: 6th July 2021

(Signature of Supervisor)

Name: Dr. Siti Harwani Binti Md. Yusoff

Date: 6th July 2021

ENDORSEMENT

I, (Sivanandini A/P Selvakone) hereby declare that all corrections and comments made by the supervisor and examiner have been taken consideration and rectified accordingly.

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Date: 6th July 2021

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Name: Dr. Siti Harwani Binti Md. Yusoff
Date: 6th July 2021

(Signature of Examiner)
Name: Dr. Norilmi Amilia Binti Ismail
Date: 6th July 2021

DECLARATION

This thesis is the result of my own investigation, except where otherwise stated and has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any other degree.

(Signature of Student)

Date: 6th July 2021

CHAPTER 1

INTRODUCTION

1.1 Research Background

It is undeniable that earthquakes have been one of the greatest catastrophes that could cause major structural damages, eventually leading to the loss of lives. Therefore, some methods to forecast the occurrence of a possible earthquake to reduce earthquake damages, and mortality rates are studied. In general, earthquake prediction seems almost impossible by solely depending on seismometer due to its limited sensitivity. However, early earthquake warning could be achieved by observing the variations in the geomagnetic fields. Any anomalous variations observed in the Earth's magnetic field can be used as a precursor for earthquakes (Vere-Jones, 1995).

Various internal and external sources could cause variations in the Earth's magnetic field. Deviations in the magnetic field due to the presence of solar wind is classified as one of the external geomagnetic variations. In contrast, the internal geomagnetic variation is usually associated with the motion of tectonic plates due to induced stress.

Previous research proposes that, prior to an earthquake, the lithospheric layers would experience an accumulated increase in stress, resulting in a shift in the geomagnetic field that can be recorded at magnetic observatories nearby. The variations in the Earth's magnetic field caused by the motions of tectonic plates can be explained through the concept of 'piezomagnetism'. Previous studies have also proven that the internal geomagnetic variation is caused by the accumulation of stress, causing remanent magnetisation within the lithospheric crust (Merrill, 1996). Thus, the idea of observing the geomagnetic variations for seismic monitoring was proposed (Wilson, 1922; Stacey, 1965; Nagata, 1970)

Studies conducted by previous researchers suggest a possible correlation between anomalous variations in geomagnetic fields and earthquakes (Yamazaki, 1970; Yamazaki, 2010). These studies have proved that the variation in the stress field can cause some major changes to the magnetic properties of the lithospheric layers (Kapicˇka, 1997). Hence, this study is conducted by observing the variations in the geomagnetic field components [North-South component (H), East-West component (D), and the Vertical component (Z)].

In general, ground-based magnetometer networks such as Magnetic Data Acquisition System (MAGDAS) and International Real-Time Magnetic Observatory Network (INTERMAGNET) have been widely used to study the Earth’s magnetic field variations for earthquake-related study. The data obtained from these geomagnetic networks will be analysed to examine the relationship between any anomalous geomagnetic field variations and seismic activities such as earthquakes.

1.1.1 Overview of MAGDAS System

MAGDAS is a real-time ground-based magnetometer network that was developed by the International Centre for Space Weather Science and Education (ICSWSE), Kyushu University with objectives to study (1) global three-dimensional current system, (2) ambient plasma density, and (3) the penetrating process of polar fields into the equatorial ionosphere (Yumoto, 2006).

Since Malaysia is located close to the geomagnetic equator, several MAGDAS stations have been set up, as shown in **Figure 1.1,** to monitor the geomagnetic components H, D, and Z (Latiff, 2019). Generally, there are three types of magnetometer systems developed by ICSWSE. However, only two types of magnetometer systems, MAG-II and MAG-9, have been installed in Malaysia.

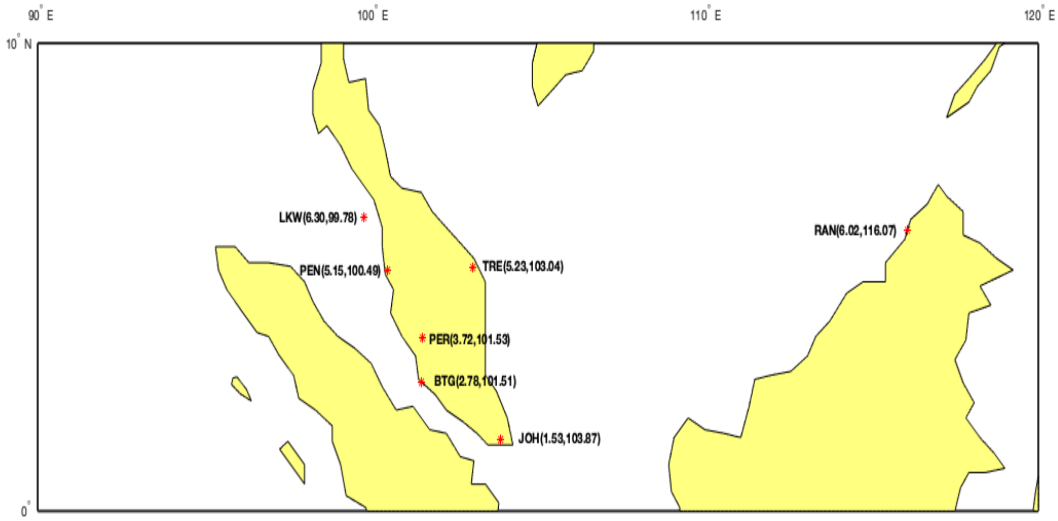

Figure 1.1: Locations of MAGDAS stations in Malaysia

The details of all the MAGDAS stations that have been installed in Malaysia are listed in **Table 1.1** below.

Table 1.1: Details of MAGDAS stations in Malaysia

Station Code	Station Name, Location	Geographic Coordinate (Lat, Long)	Geomagnetic Coordinate (Lat, Long)	Date Installed DD/MM/YY	Magnetometer Type
LKW	Langkawi, Kedah	(6.30°, 99.78°)	(-3.30°, 172.44°)	08/09/06	MAG-9
RAN	Ranau, Sabah	(6.02°, 116.07°)	(-3.56°, 188.66°)	30/03/13	MAG-9
PER	Tg Malim, Perak	(3.72°, 101.53°)	(-5.92°, 174.14°)	25/10/16	MAG-9
BTG	Banting, Selangor	(2.78°, 101.51°)	(-6.86°, 174.10°)	19/11/16	MAG-II
JOH	Pasir Gudang, Johor	(1.53°, 103.87°)	(-7.99°, 176.79°)	17/02/17	MAG-9
TRE	Gong Badak, Terengganu	(5.23°, 103.04°)	(-4.21°, 175.91°)	24/02/17	MAG-II
PEN	Nibong Tebal, Penang	(5.15°, 100.49°)	(-4.23°, 173.18°)	19/09/19	MAG-II

Both MAG-II and MAG-9 type magnetometers are equipped with three components ring fluxgate-type magnetic sensors, pre-amplifier, Global Positioning System (GPS), and data logger. However, the MAG-9 magnetometer seems more sensitive and provides accurate geomagnetic data than the MAG-II system. MAG-II records real-time variations of geomagnetic components H, D, and Z in terms of delta H (δH), delta D (δD), and delta Z (δZ) with a frequency of 16 Hz while MAG-9 logs 1 second-averaged data for (H + δH), (D + δD), and (Z + δZ), respectively at 10 Hz.

Even though there have already been seven MAGDAS stations operating effectively in Malaysia, a new MAG-II type magnetometer was recently installed in Nibong Tebal, Penang, for earthquake study. The location of this station was chosen as it is located much closer to the geomagnetic equatorial. The increase in geomagnetic stations at peninsular Malaysia will inevitably provide accurate and reliable Earth magnetic field data analysis (Zakaria, 2021).

1.1.2 Overview of MAGDAS-II System in Penang

A MAGDAS-II type magnetometer, as shown in **Figure 1.2** below, was installed at Universiti Sains Malaysia (USM) on the 19th of September 2019 to monitor Earth's magnetic field and ambient plasma density in the geo-space environment. A MAGDAS-II system consists of three orthogonal axial ring-core fluxgate magnetic sensors, an amplifier, Global Positioning System (GPS), and a data logger. The data logger functions as a power supply while controlling the communication process. Generally, the MAGDAS system detects the ambient magnetic field components H, D, and Z whereby H refers to Geomagnetic Northward, D refers to Geomagnetic Eastward, while Z refers to Vertical Downwards. However, MAG-II only records the daily variations in the ambient magnetic field components H, D, and Z as delta H (δH), delta D (δD), and delta Z (δH) for every one second (1-second) with a sampling rate of 16 Hz, respectively.

Figure 1.2: MAGDAS-II magnetometer components (Umar, et al., 2018)

Since the sensor used in the MAG-II system is very sensitive to environmental factors such as temperature, humidity, and wind speed, the magnetometer must be placed in an isolated area without any noise, human activities, or interferences (Ibrahim, 2017). Therefore, a sensor hut was developed in a deserted field more than 100 meters away from buildings and roads to minimize human activities (Jankowski, J. & Sucksdorff, C., 1996). The base of the hut was a few feet under the ground and had thick sidewalls to maintain the temperature of the sensors. The sensor was also highly insulated with bottles of water, as shown in **Figure 1.3,** to countermeasure any drifts in the temperature. The hut must be within $\pm 1°C$ of the optimum temperature value to ensure that the magnetometer functions effectively (Mahrous, 2010).

Figure 1.3: MAGDAS-II type Magnetometer installed in Penang, Malaysia, equipped with water bottles to maintain its temperature

Figure 1.4 illustrates the overall arrangement of the components at the newly established MAGDAS station in Penang, Malaysia. A small cabin was built about 60 meters away from the magnetometer to equip the data logger and GPS for safety and security purposes.

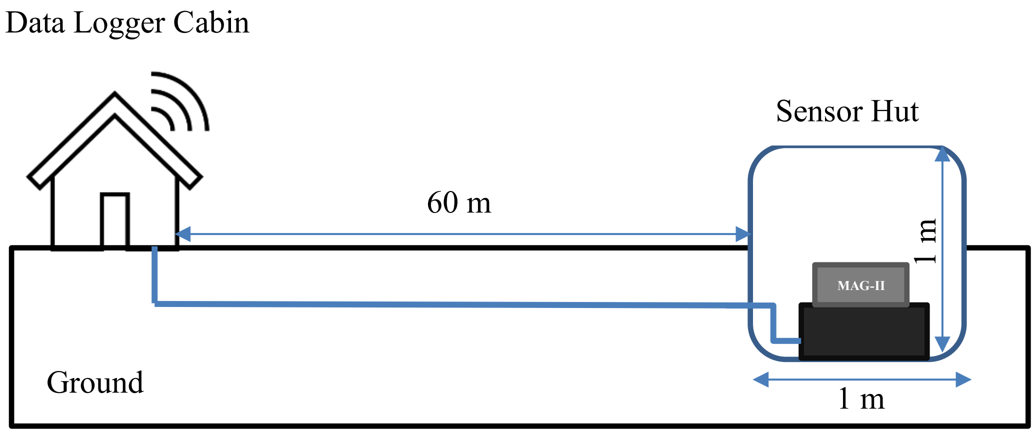

Figure 1.4: Overall Layout of MAGDAS Station at Penang, Malaysia

Figure 1.5 shows the flow of data from the sensor to the data logger. Firstly, the analogue geomagnetic signals recorded by the magnetometer will be digitised by 24 bits and 10 Hz resolution using DCR5SD analogue to digital converter at the pre-amplifier (Zakaria, 2021). The recorded data will then be stored inside the data card while automatically transferring the real-time data to ICSWSE in Japan for further analysis.

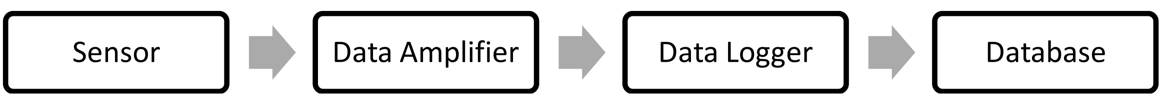

Figure 1.5: Data-Flow Diagram

1.2 Problem Statement

A MAGDAS-II type magnetometer system was recently installed at Penang for seismic monitoring. However, its reliability is yet to be configured. Therefore, the daily variation in the geomagnetic field from MAGDAS must be compared with the geomagnetic data obtained from another well-established ground-based magnetometer network. Thus, the data recorded by the MAGDAS magnetometer is compared with the INTERMAGNET system to verify its viability for earthquake study. Previous studies on earthquakes suggest that the relationship between anomalous geomagnetic variations and earthquakes can be proven by monitoring the Earth's magnetic field prior to an earthquake. This method could be one of the effective ways to predict the occurrence of an earthquake based on its seismicity. Hence, the data obtained from the MAGDAS network shall be analysed to identify the relationship between anomalous variations in geomagnetic fields and earthquakes in Sumatra.

1.3 Research Objective(s)

This research project aims:

1. To observe the reliability of the newly installed MAGDAS system for earthquake study by comparing geomagnetic data with the INTERMAGNET system
2. To observe the Earth's magnetic field during seismic activities such as Earthquakes in Sumatra Region from 2015 – 2020

1.4 Research Scope

This study focuses on:

1. The functionality of the newly installed MAGDAS magnetometer at Penang. The reliability of the magnetometer is verified by comparing daily variations of the geomagnetic field with the INTERMAGNET system
2. The role of ground-based magnetometers in monitoring Earth's magnetic field for earthquake study
3. The relationship between geomagnetic variations and earthquakes. The precursory phenomena associated with seismic activities are validated by analysing earthquake data

1.5 Research Area

The targeted area chosen for this study is Sumatra, as shown in **Figure 1.6** below. Sumatra is known to be one of the earthquake-prone regions in South-East Asia. It is located at the boundary of two tectonic plates, the Indo-Australian Plate and Eurasian Plate. The Indo-Australian plate motion would eventually disrupt the Eurasian plate, causing a shift in the geomagnetic field, leading to earthquakes. The region where these two boundary plates meet is called the Ring-of-Fire, a path along the Pacific Ocean that triggers frequent volcano eruptions and earthquakes. Therefore, a wide region in Sumatra with a range of longitude (90° ~ 120°) and latitude (10° ~ -10°) was chosen for this study.

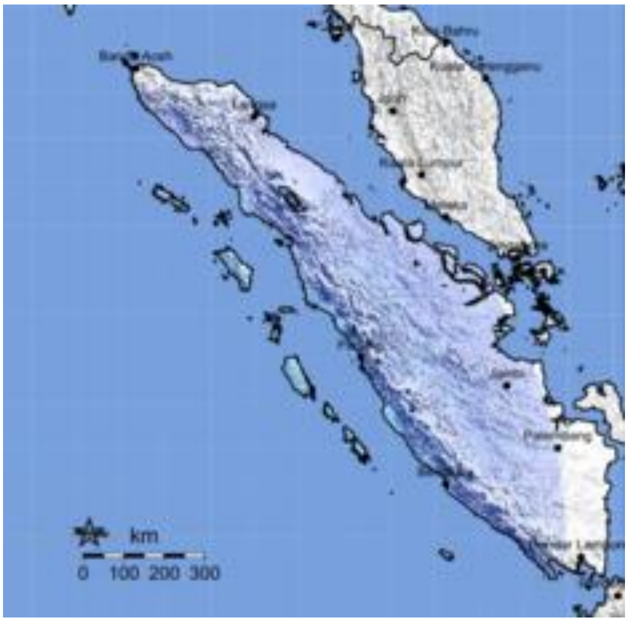

Figure 1.6: Map of Research Area (USGS National Earthquake Information Center, PDE, 2016)

1.6 Thesis Outline

In general, this thesis comprises of five main chapters.

The first chapter of this thesis briefly discusses the role of the newly installed MAGDAS-II type magnetometer at Penang in monitoring Earth's magnetic field for earthquake study. The method to validate the sensitivity and reliability of the magnetometer is described in this chapter. The problem statement and main objectives of this project are stated in this section as well.

Chapter two of this thesis provides an overview of the ground-based magnetometer networks, namely MAGDAS and INTERMAGNET, and their contribution in observing geomagnetic field variations during seismic activities. Moreover, the correlation between anomalous variations in geomagnetic fields and earthquakes that previous researchers have proposed is also discussed in this chapter.

The third chapter describes the methodology conducted for this research. The workflow to process the geomagnetic data obtained from MAGDAS and INTERMAGNET systems is provided in this section. Furthermore, the data analysis method to verify the interrelationship between Earth's magnetic field and earthquakes is also explained in this chapter. Subsequently, the procedure and programming language used to process the geomagnetic data are discussed throughout this section.

Chapters four and five present the results obtained for this study. Chapter four provides the results of geomagnetic variations acquired from both MAGDAS and INTERMAGNET stations. The results from both stations are compared and analysed to validate the sensitivity of the newly established MAGDAS station in Penang.

The following chapter, Chapter five, shows the geomagnetic variations observed prior to the earthquake. After analysing the earthquake data, the relationship between any anomalous variations in geomagnetic fields associated with earthquakes is also deduced by the end of this chapter.

Lastly, Chapter six summarises all the principal outcomes of this research. Any improvements that can be done as future work on this project are proposed in this final section.

CHAPTER 2

LITERATURE REVIEW

2.1 Ground-based magnetometer networks

Ground-based magnetometer networks such as MAGDAS and INTERMAGNET are systems equipped with arrays of magnetometers worldwide to support space weather monitoring and research. Apart from that, these magnetometer systems use to monitor the behaviour of geomagnetic components such as H, D, Z, and F. MAGDAS system consists of a large array of real-time magnetometers. The distribution of its geomagnetic stations is shown in **Figure 2.1** below.

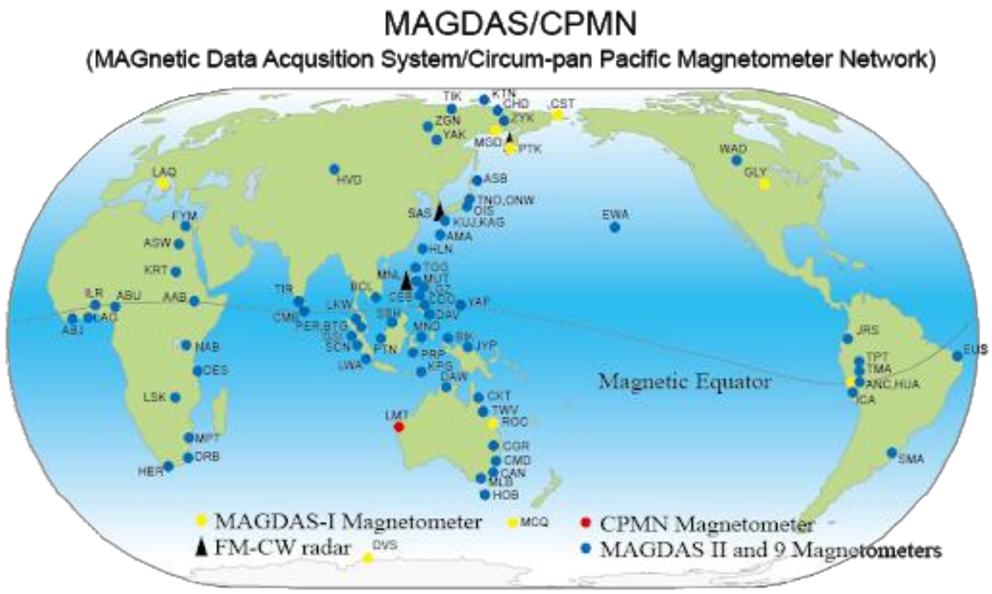

Figure 2.1: Locations of MAGDAS stations all over the world (International Center for Space Weather Science and Education (ICSWSE), Kyushu University , 2017)

MAGDAS network was developed to understand the coupling system between the Sun and the Earth and the electromagnetic and plasma environments (Yumoto, 2006). MAGDAS magnetometers are made of three-component ring-core fluxgate type of magnetic sensors used to measure the geomagnetic field components H, D, and Z, respectively. These sensors would help the magnetometer to detect even the tiniest fluctuations in the geomagnetic field. The MAGDAS magnetometer would normally record geomagnetic data every second with a sampling frequency of 16 Hz (Yusof, 2019). The geomagnetic data acquired from the MAGDAS magnetometer will be stored in a compact flash memory card and transferred to the ICSWSE in near real-time.

On the other hand, INTERMAGNET systems generally use IPGP VM391 homocentric fluxgate magnetometer, which allows three different geomagnetic field components to be measured simultaneously. The data acquired by the data logger will then be promptly reported to any operating geomagnetic information nodes in Paris, France. INTERMAGNET has also developed an open-source website whereby the public can access the geomagnetic data acquired from all the INTERMAGNET observatories worldwide. The INTERMAGNET data is also available in different formats based on the users' preferences.

2.2 Geomagnetic Field Components

Earth's magnetic field is usually represented in a three-dimensional vector which can either be expressed as geographic components of X, Y, and Z or geomagnetic components of H, D, and Z. Therefore, National Geophysical Data Centre (NGDC) suggests that the geomagnetic field consists of seven components as shown in **Figure 2.2** below. The geographic components comprise X, Y, and Z where X refers to Geographic Northward, Y refers to Geographic Eastward, and Z refers to Vertical Down (Campbell, 2003). As for the geomagnetic components of H, D, and Z, H refers to Geomagnetic Northward, D refers to Geomagnetic Eastward, while Z refers to Vertical Down. The total magnetic field intensity is expressed as vector F, whereas I stand for magnetic inclination, the angle between the horizontal plane and vector of the total magnetic field, F (Campbell, 2003). MAGDAS system usually records geomagnetic data in terms of geomagnetic components H, D, and Z while INTERMAGNET logs data as geographic components X, Y, and Z.

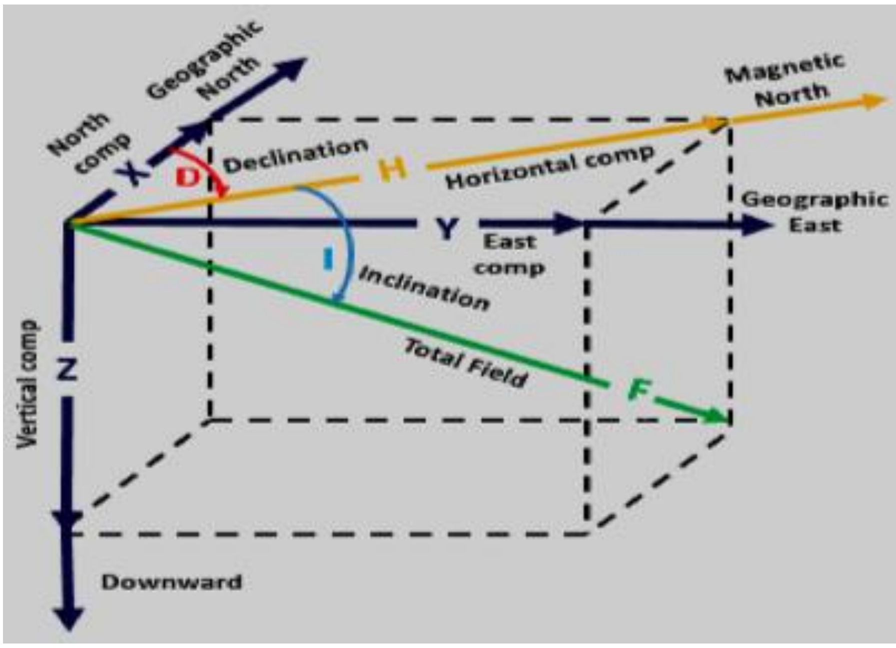

Figure 2.2: Geomagnetic field components in three-dimensional vector (Campbell, 2003)

2.3 Earthquake Precursor

Earthquakes are a phenomenon of sudden energy release caused by rock fractures. Before an earthquake occurs, the rocks found in the lithospheric layers would (Wilson, 1922)experience an accumulated increase in stress which can be recorded at nearby geomagnetic stations (Fakhrul Islam Masruri, 2017). The accumulation of stress will alter the rock's magnetic properties causing induced and remanent magnetisation within the lithospheric crust (Takla, 2013). This variation in the stress field would generate electromagnetic emissions, which will eventually cause a shift in the geomagnetic field. This process can be defined as the piezomagnetic effect whereby the tectonic process would influence the generation of anomalous geomagnetic variations (Stacey, 1965; Takla, 2013). A magnetometer from a certain distance can record these geomagnetic anomalies. Hence, the idea of monitoring geomagnetic variations was introduced by Wilson (1922) to identify the possible association between the anomalous variations in the geomagnetic field and earthquakes. Many studies have examined the relationship between geomagnetic variations and earthquakes by analysing the geomagnetic data obtained from magnetic observatories prior to an earthquake (Fakhrul Islam Masruri, 2017; Takla, 2013). Therefore, any anomalous variations observed in the geomagnetic field can be used as a precursor for earthquakes.

CHAPTER 3

METHODOLOGY

This chapter describes the data collection and data analysis processes involved in this study. The instruments that have been used to record and monitor the geomagnetic data will also be discussed in this chapter. The overall workflow of this project is also presented in this section

3.1 Geomagnetic Data Comparison

The geomagnetic data used in this research is obtained from MAGDAS and INTERMAGNET networks. The data recorded by the newly installed MAGDAS-II type magnetometer is compared with another ground-based magnetometer to validate the reliability of its data. The list of the geomagnetic stations that were chosen for this study is stated in **Table 3.1**. The INTERMAGNET station from Dalat, Vietnam, is chosen for this study. It is one of the closest and well-established magnetic observatories to the MAGDAS station in Penang, Malaysia.

Table 3.1: Details of the ground-based magnetometer networks involved in this study

Station Code	Station Name, Location	Geographic Coordinate (Lat, Long)	Geomagnetic Coordinate (Lat, Long)	Date Installed DD/MM/YY	Magnetometer Type
PEN	Penang, Malaysia	(5.15°, 100.49°)	(-4.23°, 173.18°)	19/09/19	MAG-II
DLT	Dalat, Vietnam	(11.945°, 108.482°)	(-2.46°, 178.86°)	01/04/2011	IPGP VM391

Moreover, both stations are located close to the geomagnetic equator, as shown in **Figure 3.1** below. Therefore, the geomagnetic variations obtained from both stations are most likely to have a similar pattern. The amplitude variations from both stations would also be similar because their locations are close to the geomagnetic equatorial.

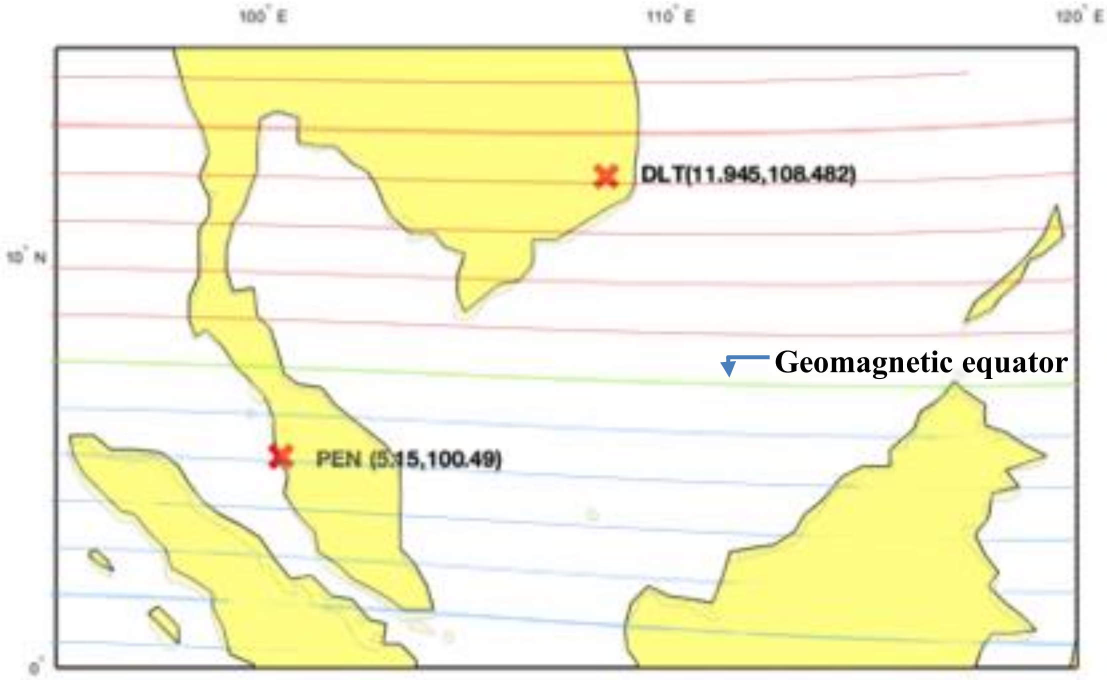

Figure 3.1: Location of magnetic observatories in Penang, Malaysia, and Dalat, Vietnam

Initially, the data obtained from the INTERMAGNET network were in terms of geographic components X, Y, and Z whereby (X) refers to Geographic Northward, (Y) refers to Geographic Eastward, and (Z) refers to Vertical Down. Therefore, the geographic components, XYZ obtained from INTERMAGNET, must be converted to geomagnetic components, HDZ to match with the data provided by MAGDAS for further analysis. Therefore, this study analysed nine months' worth of geomagnetic data obtained from both networks, whereby the research period was from November 2019 to July 2020. The variation of each geomagnetic component H, D, and Z is obtained directly from the MADGAS station in Penang, whereas the real-time data for the geomagnetic field components X, Y, and Z is accessed from the INTERMAGNET website. The data obtained from both sources shall be analysed using MATLAB software to observe the profile of the geomagnetic field.

As stated in **Table 3.1**, the MAGDAS station in Penang, Malaysia, uses a MAG-II type magnetometer consisting of three axial ring fluxgate-type magnetic sensors. The sensor records the geomagnetic variations of magnetic field components H, D, and Z as delta H (δH), delta D (δD), and delta Z (δZ) with a sampling rate of 16 Hz every second. Meanwhile, the INTERMAGNET station from Dalat, Vietnam, uses the IPGP VM391 sensor, as shown in **Figure 3.2,** which produces vector data every second with a frequency of 1 Hz. The data acquired from the INTERMAGNET website were presented in terms of geographic components X, Y, and Z as (X + δX), (Y + δY), and (Z + δZ). Hence, the geographic components X and Y obtained from INTERMAGNET must be converted to geomagnetic components H and D using **Equations 3.1 and 3.2** to compare with the geomagnetic data acquired from MAGDAS. The D_{AV} in the equations below refers to the Declination Angle, the angle between the Geographic Northward, X and Geomagnetic Northward, H.

$$H = X \cos D_{AV} + Y \sin D_{AV} \tag{3.1}$$

$$D = Y \cos D_{AV} - X \sin D_{AV} \tag{3.2}$$

Figure 3.2: IPGP VM391 Fluxgate Magnetometer used at Dalat, Vietnam (Chulliat & Anisimov, 2008)

Since INTERMAGNET magnetometer logs data as (X + δX), (Y + δY), and (Z + δZ), the variation of each geomagnetic component can be determined by subtracting the value of each element at local time ($H_{LT}, D_{LT}, and\ Z_{LT}$) with its average value of four local night-time hours (0000, 0100, 2200, and 2300) as a baseline $\left(\left[\frac{\sum H_n}{4}\right], \left[\frac{\sum D_n}{4}\right], and\ \left[\frac{\sum Z_n}{4}\right]\right)$. The method to find the geomagnetic variations of H, D, and Z ($\delta H, \delta D, \delta Z$) can be represented as **Equations 3.3, 3.4,** and **3.5**, respectively.

$$\delta H_{LT} = H_{LT} - \left(\frac{H_{00} + H_{01} + H_{22} + H_{23}}{4}\right) \tag{3.3}$$

$$\delta D_{LT} = D_{LT} - \left(\frac{D_{00} + D_{01} + D_{22} + D_{23}}{4}\right) \tag{3.4}$$

$$\delta Z_{LT} = Z_{LT} - \left(\frac{Z_{00} + Z_{01} + Z_{22} + Z_{23}}{4}\right) \tag{3.5}$$

3.2 Earthquake Study

3.2.1 Research Area

The area that was chosen for this study is Sumatra, as it is situated along the boundary of two tectonic plates, whereby the motion of one tectonic plate would disrupt the other. This would cause a shift in the geomagnetic field, triggering frequent volcano eruptions and earthquakes. Therefore, Sumatra seemed to be the perfect place for this research. The research area is from 10.00° North to -10.00° North and 90° East to 120° East. The wideness of the research area was highly influenced by the distance from the earthquake's epicentre and the availability of geomagnetic data. This study used geomagnetic data obtained from the MAGDAS station located at Langkawi (LKW) because it is one of the closest Malaysian MAGDAS stations to the earthquake's epicentre. The details of the geomagnetic station used in this study are shown in **Table 3.2** below.

Table 3.2: Details of MAGDAS station in Langkawi, Malaysia

Station Code	**Station Name, Location**	**Geo-graphic Coordinate (Lat, Long)**	**Geo-magnetic Coordinate (Lat, Long)**	**Date Installed DD/MM/YY**	**Magnetometer Type**
LKW	Langkawi, Kedah	(6.30°, 99.78°)	(-3.30°, 172.44°)	08/09/06	MAG-9

This study mainly focuses on the earthquake that occurred in Sumatra from 2015 to 2020. However, only the earthquake that occurred on the 2nd of March 2016 was chosen for this study. The earthquake with a Richter scale of 7.8 Mw is considered strong enough to destroy 160 km in radius. **Table 3.3** shows all the earthquake data gathered from BMKG's earthquake data repository for this research.

Table 3.3: Details of Earthquakes occurred at Sumatra from 2015 to 2020

Location	**Origin Time (UTC)**	**Magnitude (Mw)**	**Depth (km)**	**Coordinate (°)**	
				Latitude	**Longitude**
Solok, West Sumatra	July 21, 2018	5.5	10	-0.97	100.7
Mentawai Islands, Southwest of Sumatra	Mar 2, 2016	7.8	10	-4.92	94.39
Aceh, North-East Coast of Sumatra	Dec 7, 2016	6.4	10	5.19	96.36

The following **Figure 3.3** shows the distance between the geomagnetic station and the epicentre of the earthquake whereby both the geomagnetic station and the epicentre of the earthquake are marked with a star, respectively for reference.

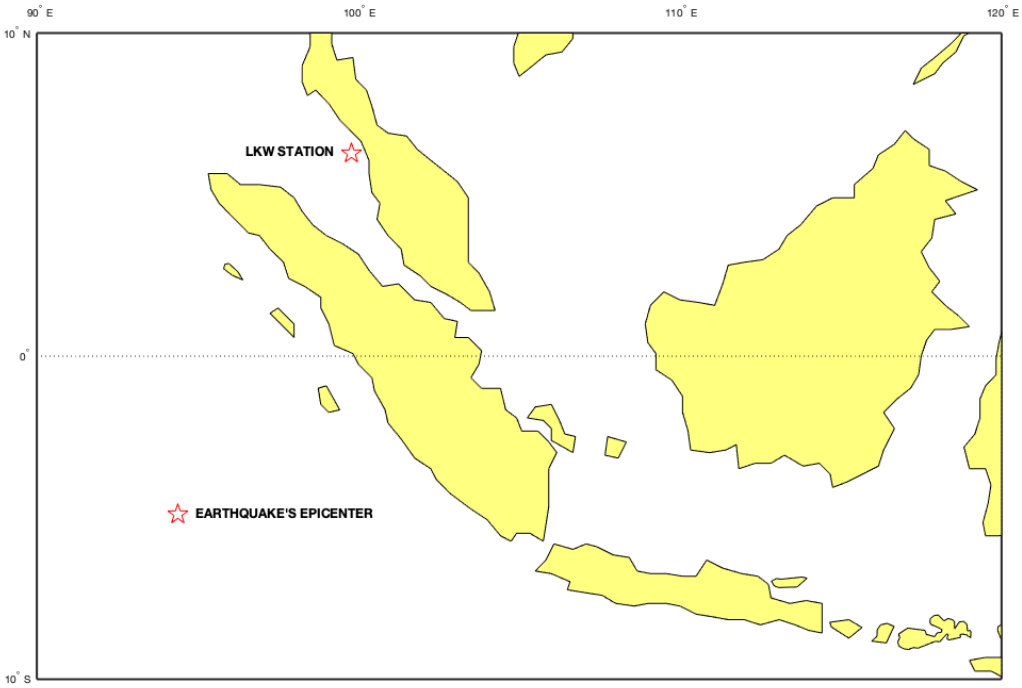

Figure 3.3: Location of Earthquake's epicentre and MAGDAS station at Langkawi

3.2.2 Instrument

The geomagnetic data obtained for this earthquake study is from the MAGDAS-9 type magnetometer installed at Langkawi, Malaysia (LKW). MAGDAS-9 measures the ambient magnetic field components HDZ in terms of (H + δH), (D + δD), and (Z + δZ) by using its three-axial flux-gate sensors respective for each independent vector. The specifications of the MAGDAS-9 type magnetometer are stated in **Table 3.4.**

Table 3.4: Specifications of MAGDAS-9 Type Magnetometer

MAGDAS-9 Type Magnetometer Specifications	
Magnetometer Type	Three-axial Flux-gate sensor
Accuracy	0.1 nT
Sampling Rate	10 Hz
Range	$\pm$70000 nT
Data Format	(H + δH), (D + δD), and (Z + δZ)
Data Interval	1-second

3.2.3 Data Analysis

Since MAGDAS-9 type magnetometer in LKW records data in terms of (H + δH), (D + δD), and (Z + δZ), the variation in the geomagnetic field is computed by identifying the baseline values of H_b, D_b, and Z_b first. The baseline values of H, D, and Z components can be determined by finding the average values of four local night-time hours (0000, 0100, 2200, and 2300) of each component mentioned in the following **Equations 3.6, 3.7,** and **3.8** (Bello, 2019; Zakaria, 2021)**.**

$$H_b = \frac{H_{22} + H_{23} + H_{00} + H_{01}}{4} \tag{3.6}$$

$$D_b = \frac{D_{22} + D_{23} + D_{00} + D_{01}}{4} \tag{3.7}$$

$$Z_b = \frac{Z_{22} + Z_{23} + Z_{00} + Z_{01}}{4} \tag{3.8}$$

The variation in each geomagnetic component of H, D, and Z ($\delta H_{LT}, \delta D_{LT}, \delta Z_{LT}$) can be determined by finding the difference between the local time values (H_{LT}, D_{LT} , Z_{LT}) and baseline value (H_b, D_b, Z_b) respectively, as shown in the following **Equations 3.9, 3.10,** and **3.11**. The subtraction of local time value with its baseline value for each component is necessary as the ionospheric currents are considered weak during midnight, causing the disappearance of the conducting E-layer (Yamazaki, 2014). Apart from that, the ionospheric current will not be assumed zero during night-time at high latitude regions due to auroral electrojet. (Yamazaki, 2017). Therefore, the baseline method is only necessary and applicable at equatorial and lower latitude regions (Zakaria, 2021).