Project Report On

THE DEVELOPMENT OF MATLAB CODE FOR THE ANALYSIS OF MAGNETOMETER DATA

Submitted to

MAHATMA GANDHI UNIVERSITY

in partial fulfilment of the requirements of the degree of

BACHELOR OF SCIENCE

in

PHYSICS

Submitted by

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Under the Guidance of

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2017 - 2020

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CERTIFICATE

This is to certify that the dissertation entitled **"THE DEVELOPMENT OF MATLAB CODE FOR THE ANALYSIS OF MAGNETOMETER DATA"** Submitted by **Mr. Albin P James, Reg No: 11701099**, is a bona fide record of the work based on the investigation carried out by them at **St. Berchmans College**, Changanassery under the guidance of **Dr Lijo Jose** in partial fulfilment of the requirement for the award of **Bachelor of Science in Physics** of **Mahatma Gandhi University**, Kottayam, during the academic year **2017-2020**.The work presented in this report has not been submitted for any degree or diploma earlier.

Dr Shajo Sebastian
Head Of Department

Dr Lijo Jose
Project Guide

DECLARATION

I hereby declare that the project report entitled "**THE DEVELOPMENT OF MATLAB CODE FOR THE ANALYSIS OF MAGNETOMETER DATA**" is an authentic report of the project work carried out by me under the guidance of Dr. Lijo Jose, Assistant Professor, Department of Physics, St. Berchmans College, Changanassery. This project work is submitted to Mahatma Gandhi University, in the partial fulfilment of the requirements for the award of the Degree of Bachelors of Science in Physics.

Albin P James

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Albin P James
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CONTENTS

Abstract

The project aims to develop a MATLAB program to analyse the magnetometer data, specifically the raw data from Sensys FGM3D TD magnetometer. Subsequently using it to study the effect of the solar eclipse occurred on 26th December, on the ionospheric contribution to the total magnetic field at Kannur and Changanassery.

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Chapter 1
Basics of Ionosphere

1.1. Atmosphere

The Earth's atmosphere extends many hundreds of kilometres out from its surface and the gravitational force of the earth keeps its earthbound. The atmosphere is denser at the surface and gets progressively rarefied with increasing altitude. The most abundant constituents in the Earth's atmosphere are molecular nitrogen (78%), molecular oxygen (21%) and carbon dioxide (0.03%) with small but varying amounts of water vapor and various trace gases. All the atmospheric constituents are well mixed up to ~100 km by turbulence, hence this region is known as the turbosphere or homosphere. At around ~110 km, the turbulence ceases and this altitude is known as the turbopause. Above this altitude, different atmospheric constituents are distributed according to their atomic/molecular weight and this region is known as the heterosphere. Based on the altitudinal extent, atmosphere has been broadly classified as lower atmosphere (0-15 km), middle atmosphere (15-90 km) and upper atmosphere (above 90 km).

The solar radiation is the primary driver of the energetics and dynamics of the atmosphere. A variety of chemical reactions involving the atmospheric constituents occur at different heights throughout the atmosphere. Various atmospheric constituents directly absorb the incoming solar radiation and redistribute the energy by radiation, conduction, convection and emission. This gives the atmosphere a characteristic vertical temperature structure, which is shown in Figure 1.1. According to the process of heating involved, atmosphere can be classified as troposphere (0-15 km), stratosphere (15-50 km), mesosphere (50-90 km) and thermosphere (above 90 km). In the troposphere, the heating is through absorption of infrared radiation by water vapor, carbon dioxide and ozone. The temperature falls off at a rate of ~10 K/km in vertical direction till its upper boundary tropopause. Above tropopause, the temperature again starts increasing due to the absorption of ultraviolet (UV) radiation (<2800 Å) by ozone. In this region, the maximum heating appears at ~50 km height and is called the stratopause. Above this, the temperature again decreases with height in the mesosphere to a minimum at the mesopause (~80-85 km) which is the coldest part (~ 180 K) of the atmosphere. The existence of temperature minimum in this altitude is due to the lack of strong heating mechanism and also due to radiative cooling through emission of infrared and visible airglow. In the thermosphere, temperature increases drastically due to the absorption of extreme ultra-violet (EUV) radiation (100-1000 Å). In the upper thermosphere, the thermal conductivity enhances such that this region is maintained in a nearly isothermal condition, at a relatively high temperature, that varies between 1000-2000 K depending on the phase of the solar cycle.

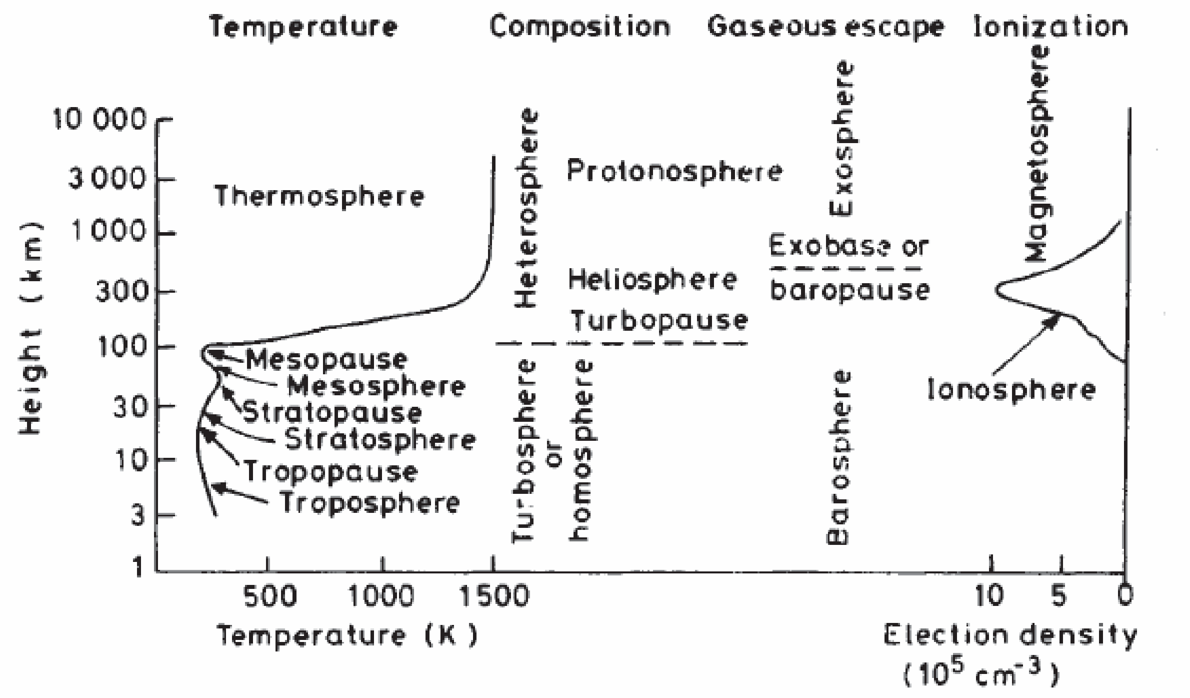

Figure 1.1 *Nomenclature of the upper atmosphere based on temperature, composition, mixing and ionization [After Hargreaves, 1992].*

In the heterosphere, there are regions where lighter gases like helium and hydrogen is abundant. These are called heliosphere and the protonosphere respectively. Above about 600 km, collision becomes so infrequent that the individual neutral atoms can move in ballistic orbits and can escape to the outer space. This region is called exosphere. The base of the exosphere is the exobase or the baropause. However, ionized particles cannot move freely and are constrained to the geomagnetic field. This region where the earth's magnetic field controls the dynamics of the atmosphere is called magnetosphere. The upper boundary of magnetosphere called magnetopause, which separates the solar wind from earth's geomagnetic field. The magnetosphere has no well-defined lower boundary, though the exobase is sometimes considered so. The ionized region of the atmosphere that extends from the base of mesosphere to the base of magnetosphere is collectively known as ionosphere. It is defined as the part of upper atmosphere in which electrons and ions are present in sufficient numbers to affect the propagation of radio waves [Rishbeth and Garriott, 1969; Banks and Kockarts, 1973; Kelley, 1989; Hargreaves, 1992]. The ionosphere itself is divided into different regions or layers based on its origin. The following section gives the history and discusses the mechanism of production of ionospheric layers.

1.2. Formation of Ionosphere, D, E and F region

High-energy X-rays and ultraviolet (UV) "light" from the Sun are constantly colliding with gas molecules and atoms in Earth's upper atmosphere. Some of these collisions knock electrons free from the atoms and molecules, creating electrically charged ions (atoms or molecules with missing electrons) and free electrons. These electrically charged ions and electrons move and behave differently than normal, electrically neutral atoms and molecules. Regions with higher concentrations of ions and free electrons occur at several different altitudes and are known, as a group, as the ionosphere.

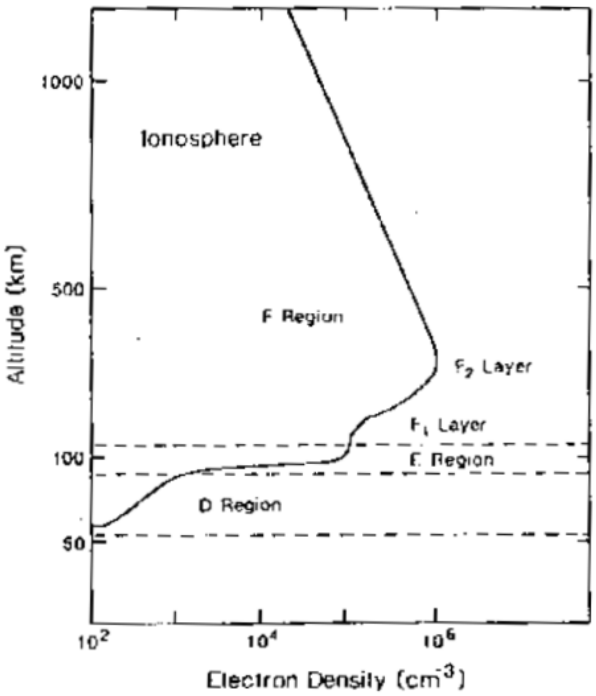

Figure 1.2 *Typical plasma density profile of Earth's ionosphere, showing the D, E, and F layers, as functions of altitude [Brand, 1998].*

There are three main regions of the ionosphere, called the D layer, the E layer, and the F layer. These regions do not have sharp boundaries, and the altitudes at which they occur vary during the course of a day and from season to season. The D region is the lowest, starting about 60 or 70 km (37 or 43 miles) above the ground and extending upward to about 90 km (56 miles). Next higher is the E region, starting at about 90 or 100 km (56 or 62 miles) up and extending to 120 or 150 km (75 or 93 miles). The uppermost part of the ionosphere, the F region, starts about 150 km (93 miles) and extends far upward, sometimes as high as 500 km (311 miles) above the surface of our home planet.

The regions of the ionosphere are not considered separate layers, such as the more familiar troposphere and stratosphere. Instead, they are ionized regions embedded within the standard atmospheric layers. The D region usually forms in the upper part of the mesosphere, while the E region typically appears in the lower thermosphere and the F region is found in the upper reaches of the thermosphere. The geomagnetic field plays an important role in the ionospheric currents.

1.3. Geomagnetic field formation

Although the Earth's magnetic field resembles that of a bar magnet we must find another explanation for the field's origin. Permanent magnets cannot exist at the temperatures found in the Earth's core. We also know that the Earth has had a magnetic field for hundreds of millions of years. We cannot, however, simply attribute the existence of the present geomagnetic field to some event in the distant past. Magnetic fields decay, and we can show that the existing geomagnetic field would disappear in about 15,000 years unless there were a mechanism to continually regenerate it.

Many mechanisms have been postulated to explain how the magnetic field is generated, but the only one that is now considered plausible is analogous to a dynamo, or generator - a devise for converting mechanical energy to electrical energy. To understand how a dynamo would work in the context of the Earth, we need to understand the physical conditions in the Earth's interior.

The Earth is composed of layers: a thin outer crust, a silicate mantle, an outer core and an inner core. Both temperature and pressure increase with depth within the Earth. The temperature at the core mantle boundary is roughly 4800° C, hot enough for the outer core to exist in a liquid state. The inner core, however, is solid because of increased pressure. The core is composed primarily of iron, with a small percentage of lighter elements. The outer core is in constant motion, due both to the Earth's rotation and to convection. The convection is driven by the upward motion of the light elements as the heavier elements freeze onto the inner core.

The actual process by which the magnetic field is produced in this environment is extremely complex, and many of the parameters required for a complete solution of the mathematical equations describing the problem are poorly known. However, the basic concepts are not difficult. For magnetic field generation to occur several conditions must be met:

1. there must be a conducting fluid;

2. there must be enough energy to cause the fluid to move with sufficient speed and with the appropriate flow pattern;
3. there must be a "seed" magnetic field.

All these conditions are met in the outer core. Molten iron is a good conductor. There is sufficient energy to drive convection, and the convective motion, coupled with the Earth's rotation, produce the appropriate flow pattern. Even before the Earth's magnetic field was first formed magnetic fields were present in the form of the sun's magnetic field. Once the process is going, the existing field acts as the seed field. As a stream of molten iron passes through the existing magnetic field, an electric current is generated through a process called magnetic induction. The newly created electric field will in turn create a magnetic field. Given the right relationship between the magnetic field and the fluid flow, the generated magnetic field can reinforce the initial magnetic field. As long as there is sufficient fluid motion in the outer core, the process will continue.

1.4. Feature of the geomagnetic field

The Earth acts like a large spherical magnet: it is surrounded by a magnetic field that changes with time and location. The field is generated by a dipole magnet (i.e., a straight magnet with a north and south pole) located at the center of the Earth. The axis of the dipole is offset from the axis of the Earth's rotation by approximately 11 degrees. This means that the north and south geographic poles and the north and south magnetic poles are not located in the same place. At any point and time, the Earth's magnetic field is characterized by a direction and intensity which can be measured. Often the parameters measured are the magnetic declination, D, the horizontal intensity, H, and the vertical intensity, Z. From these elements, all other parameters of the magnetic field can be calculated.

The geomagnetic field measured at any point on the Earth's surface is a combination of several magnetic fields generated by various sources. These fields are superimposed on and interact with each other. More than 90% of the field measured is generated INTERNAL to the planet in the Earth's outer core. This portion of the geomagnetic field is often referred to as the Main Field. The Main Field varies slowly in time and can be described by mathematical models such as the International Geomagnetic Reference Field (IGRF) and World Magnetic Model (WMM). The Earth's Main Field dominates over the interplanetary magnetic field in the area called the magnetosphere. The magnetosphere is shaped somewhat like a comet in response to the dynamic pressure of the solar wind. It is compressed on the side toward the sun to about 10 Earth radii and is extended tail-like on the side away from the sun to more than 100 Earth radii. The magnetosphere deflects the flow of most solar wind particles around the Earth, while the geomagnetic field lines guide charged particle motion within the magnetosphere. The differential flow of ions and electrons inside the magnetosphere and in the ionosphere form current systems, which cause variations in the intensity of the Earth's magnetic field. These EXTERNAL currents in the ionized upper atmosphere and magnetosphere vary on a much shorter time scale than the INTERNAL Main Field and may create magnetic fields as large as 10% of the Main Field.

To measure the Earth's magnetism in any place, we must measure the direction and intensity of the field. The Earth's magnetic field is described by seven parameters. These are declination (D), inclination (I), horizontal intensity (H), the north (X) and east (Y) components of the horizontal intensity, vertical intensity (Z), and total intensity (F). The parameters describing the direction of the magnetic field are declination (D) and inclination (I). D and I are measured in units of degrees, positive east for D and positive down for I. The intensity of the total field (F) is described by the horizontal component (H), vertical component (Z), and the north (X) and east (Y) components of the horizontal intensity. These components may be measured in units of gauss but are generally reported in nanoTesla (1nT * 100,000 = 1 gauss). The Earth's magnetic field intensity is roughly between 25,000 - 65,000 nT (.25 - .65 gauss). Magnetic declination is the angle between magnetic north and true north. D is considered positive when the angle measured is east of true north and negative when west. Magnetic inclination is the angle between the horizontal plane and the total field vector, measured positive into Earth. In older literature, the term “magnetic elements” often referred to D, I, and H.

The magnetic field is different in different places. In fact, the magnetic field changes with both location and time. It is so irregular that it must be measured in many places to get a satisfactory picture of its distribution. This is done using satellites, and approximately 200 operating magnetic observatories worldwide, as well as several more temporary sites. However, there are some regular features of the magnetic field. At the magnetic poles, a dip needle stands vertical (dip=90 degrees), the horizontal intensity is zero, and a compass does not show direction (D is undefined). At the north magnetic pole, the north end of the dip needle is down; at the south magnetic pole, the north end is up. At the magnetic equator the dip or inclination is zero. Unlike the Earth's geographic equator, the magnetic equator is not fixed, but slowly changes.

The magnetic poles are defined as the area where dip (I) is vertical. You can compute this area using magnetic field models, such as the World Magnetic Model (WMM) and the International Geomagnetic Reference Field (IGRF). You can also survey for the magnetic pole, using instruments that measure the magnetic field strength and direction. In practice, the geomagnetic field is not exactly vertical at these poles, but is vertical on oval-shaped loci traced on a daily basis, with considerable variation from one day to another, and approximately centered on the dip pole positions. Magnetic declination (D) is unreliable near the poles.

The magnetic equator is where the dip or inclination (I) is zero. There is no vertical (Z) component to the magnetic field. The magnetic equator is not fixed, but slowly changes. North of the magnetic equator, the north end of the dip needle dips below the horizontal, I and Z are positive. South of the magnetic equator, the south end dips below the horizontal, I and Z are measured negative. As you move away from the magnetic equator, I and Z increase.

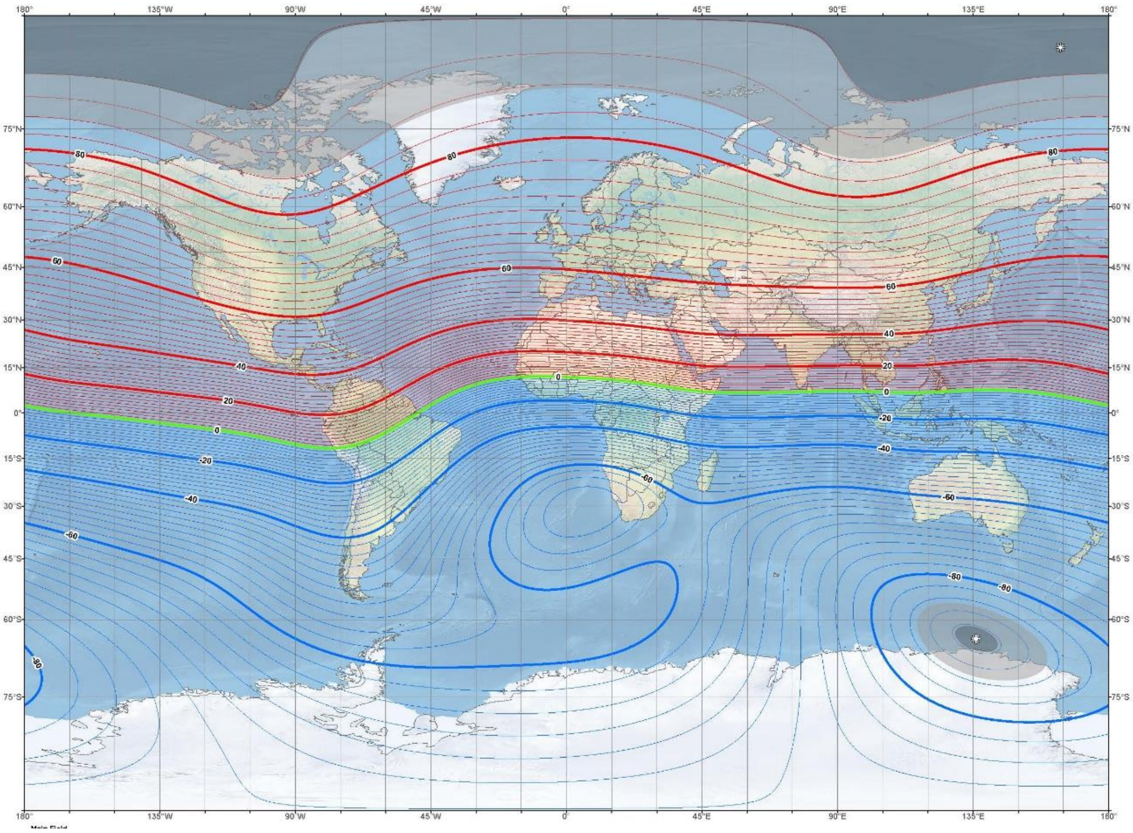

Figure 1.3 *This image shows the magnetic equator in green [Map developed by NOAA/NCEI and CIRES, 2019].*

There are many different definitions of geomagnetic coordinates. The simplest is to take the location of the geomagnetic dipole then do a coordinate transformation from coordinates centered on the geographic pole to coordinates centered on the dipole. Longitude 0 is defined as the imaginary line from the geographic north pole to the geomagnetic north dipole.

1.5. Equatorial Ionosphere

The equatorial ionosphere is defined as the region between ±20^{o} geomagnetic latitudes and extending from 60km to 2000km. The equatorial ionosphere is one important part of the ionosphere-magnetosphere plasma environment of the earth. Its importance derives from the scientifically fascinating phenomena occurring in this region of space and also from the practical implications of the phenomena to the communication circuits involving the propagation of signals through this media.

Most of the special features of equatorial ionosphere can be considered as subsets of three major phenomena: (i) the Equatorial Spread F (ESF) (ii) the Equatorial Electrojet (EJJ) and (iii) the Equatorial Anomaly (EA). All three phenomena in turn result from the orthogonality of the almost horizontal geomagnetic field lines and the electric fields threading the ionosphere in the vicinity of the dip equator. Studies in the past five decades have revealed the fascinating and bewildering complexity of the equatorial phenomenon.

1.6. Earth’s magnetosphere

A magnetosphere is the region around a planet dominated by the planet's magnetic field. Other planets in our solar system have magnetospheres, but Earth has the strongest one of all the rocky planets: Earth's magnetosphere is a vast, comet-shaped bubble, which has played a crucial role in our planet's habitability. Life on Earth initially developed and continues to be sustained under the protection of this magnetic environment. The magnetosphere shields our home planet from solar and cosmic particle radiation, as well as erosion of the atmosphere by the solar wind - the constant flow of charged particles streaming off the sun.

Earth's magnetosphere is part of a dynamic, interconnected system that responds to solar, planetary, and interstellar conditions. It is generated by the convective motion of charged, molten iron, far below the surface in Earth's outer core. Constant bombardment by the solar wind compresses the sun-facing side of our magnetic field. The sun-facing side, or dayside, extends a distance of about six to 10 times the radius of the Earth. The side of the magnetosphere facing away from the sun - the nightside - stretches out into an immense magnetotail, which fluctuates in length and can measure hundreds of Earth radii, far past the moon's orbit at 60 Earth radii.

The shape of the Earth's magnetosphere is the direct result of being blasted by solar wind. The solar wind compresses its sunward side to a distance of only 6 to 10 times the radius of the Earth. A supersonic shock wave is created sunward of Earth called the Bow Shock. Most of the solar wind particles are heated and slowed at the bow shock and detour around the Earth in the Magnetosheath. The solar wind drags out the night-side magnetosphere to possibly 1000 times Earth's radius; its exact length is not known. This extension of the magnetosphere is known as the Magnetotail. The outer boundary of Earth's confined geomagnetic field is called the Magnetopause. The Earth's magnetosphere is a highly dynamic structure that responds dramatically to solar variations.

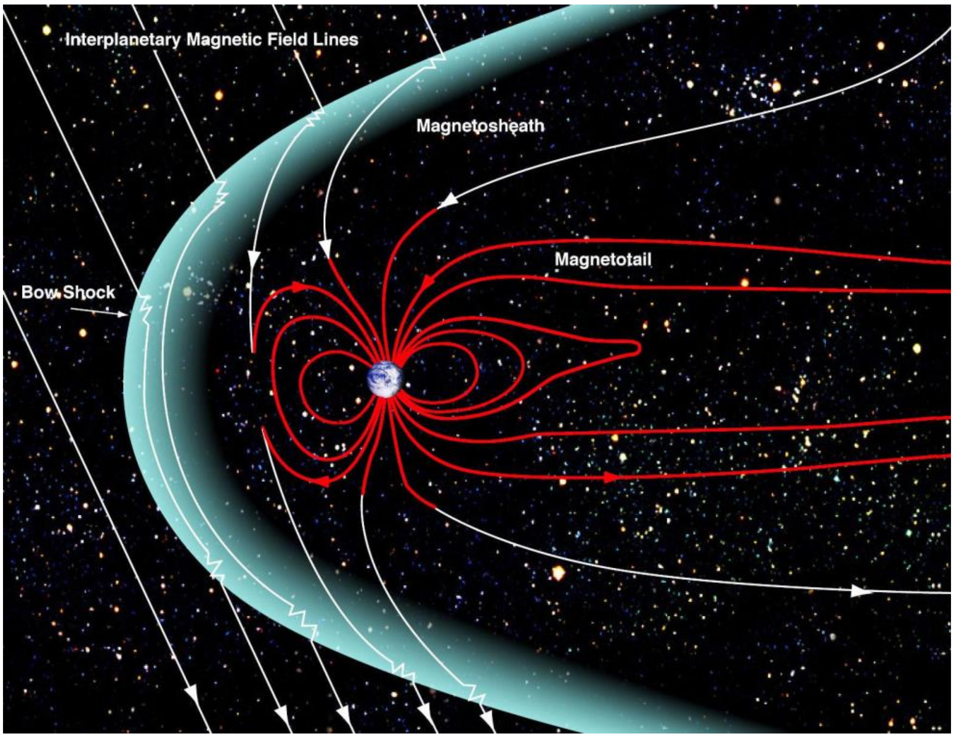

Figure 1.4 *This image shows the earth's magnetosphere[*NASA/Goddard/Aaron Kaase*].*

Conclusion:

It is evident from the above discussions the various layers of the atmosphere, how the ionosphere forms, how the earth's magnetic fields influence it and the specialities of the equatorial region of the ionosphere.

Chapter 2

Instrumentation and development of MATLAB Code

2.1. Measuring Geomagnetic fields

Science begins with the observation of the real world. Scientists believe in something only if they can sense that physical quantity with their own sensory organs or using a sensing instrument. This means that without observations science is nothing but philosophy. The history of science shows that new methods, novel techniques and new ideas always bring great advances in knowledge. The study of ionosphere was a stepping stone towards space science and later to space exploration. Historically, ionosphere has been probed by a variety of ground based instruments such as a ground-based ionosonde, incoherent scatter radar and coherent backscatter radar. Later, in-situ measurements using the satellite and rocket based probes have been used extensively. Today with the increased dependency on satellites for civil aviation/navigation purpose, the need of predicting the ionospheric parameters to the desired accuracy has become an important task. In order to cater to this particular need, the characterization of many complex phenomena that exist in the ionosphere which show day-to-day, seasonal and solar cycle variablities has become imperative. Today, it is very well realized that one cannot account for all the variablites in the ionosphere without addressing to the contribution that are of lower atmospheric in origin. This realization has triggered a whole new class of ionospheric studies coupling it with other regions of atmosphere like the mesosphere or magnetosphere. In this scenario, though single point measurements with a single instrument are still considered important, but are definitely regarded as inadequate. The ionosphere being a very wide and complex system, each instrument can give only partial reality or half-truths. As a consequence, one requires multiple instruments and multi-point observations to effectively study the ionosphere in all its complexity.

There are two types of magnetometers that have been used to study the daily variation of geomagnetic field. These are (1) a Protron Precession Magnetometer (PPM) (for measuring the total magnetic field intensity at a given location) and (2) a three axis Flux Gate Magnetometer (FGM) (for measuring the magnetic field intensity in three given directions).

2.1.1. Proton Precession Magnetometer (PPM) Theory

A proton magnetometer, also known as a proton precession magnetometer (PPM), uses the principle of Earth's field nuclear magnetic resonance (EFNMR) to measure very small variations in the Earth's magnetic field, allowing ferrous objects on land and at sea to be detected.

PPMs were once widely used in mineral exploration. They have largely been superseded by Overhauser effect magnetometers and alkali vapour (cesium, rubidium, and potassium) or helium magnetometers, which sample faster and are more sensitive.

A direct current flowing in a solenoid creates a strong magnetic field around a hydrogen-rich fluid (kerosine and decane are popular, and even water can be used), causing some of the protons to align themselves with that field. The current is then interrupted, and as protons realign themselves with the ambient magnetic field, they precess at a frequency that is directly proportional to the magnetic field. This produces a weak rotating magnetic field that is picked up by a (sometimes separate) inductor, amplified electronically, and fed to a digital frequency counter whose output is typically scaled and displayed directly as field strength or output as digital data.

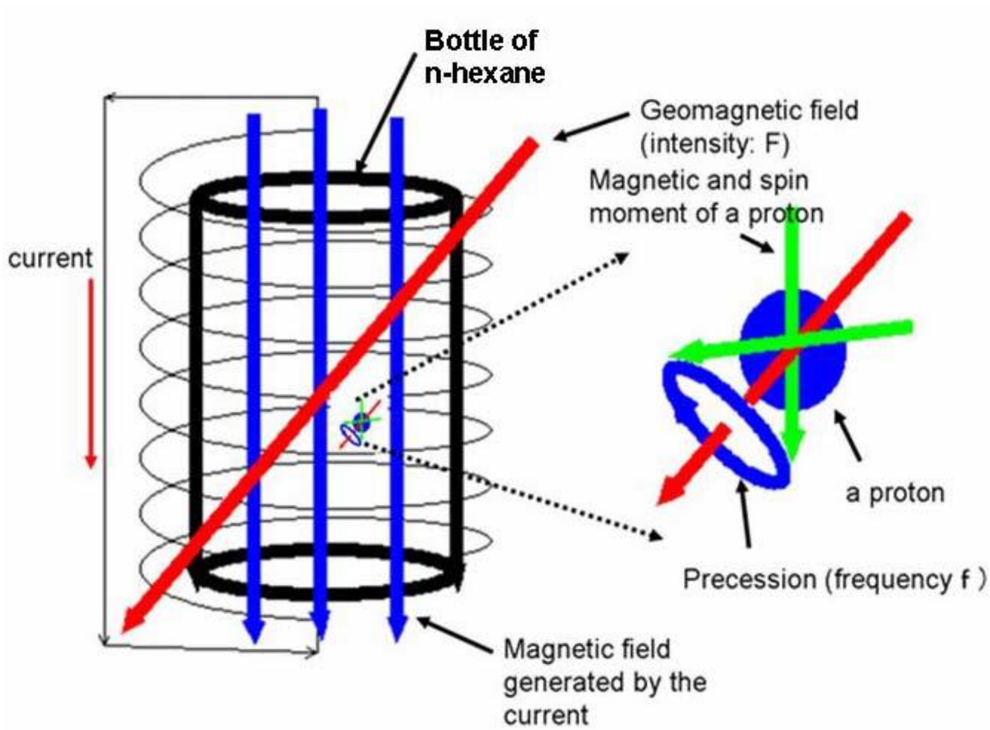

***Figure 2.1** The experimental setup for a Proton precession magnetometer. In the right hand side, the precession of a proton about the geomagnetic field immediately after the switching off of external magnetic field is illustrated.*

The relationship between the frequency of the induced current and the strength of the magnetic field is called the proton gyromagnetic ratio, and is equal to 0.042576 Hz nT^{-1}. Because the precession frequency depends only on atomic constants and the strength of the ambient magnetic field, the accuracy of this type of magnetometer can reach 1 ppm.

The frequency of Earth's field NMR for protons varies between approximately 900 Hz near the equator to 4.2 kHz near the geomagnetic poles. These magnetometers can be moderately sensitive if several tens of watts are available to power the aligning process. If measurements are taken once per second, standard deviations in the readings is in the 0.01 nT to 0.1 nT range, and variations of about 0.1 nT can be detected.

For hand/backpack carried units, PPM sample rates are typically limited to less than one sample per second. Measurements are typically taken with the sensor held at fixed locations at approximately 10 meter increments.

The main sources of measurement errors are magnetic impurities in the sensor, errors in the measurement of the frequency and ferrous material on the operator and the instruments, as well as rotation of the sensor as a measurement is taken.

Portable instruments are also limited by sensor volume (weight) and power consumption. PPMs work in field gradients up to 3,000 nT m−1 which is adequate from most mineral exploration work. For higher gradient tolerance such as mapping banded iron formations and detecting large ferrous objects Overhauser magnetometers can handle 10,000 nT m−1 and Caesium magnetometers can handle 30,000 nT m−1.

2.1.2. Flux gate magnetometer

The fluxgate magnetometer was invented by H. Aschenbrenner and G. Goubau in 1936 . A team at Gulf Research Laboratories led by Victor Vacquier developed airborne fluxgate magnetometers to detect submarines during World War II and after the war confirmed the theory of plate tectonics by using them to measure shifts in the magnetic patterns on the sea floor.

A fluxgate magnetometer consists of a small magnetically susceptible core wrapped by two coils of wire. An alternating electric current is passed through one coil, driving the core through an alternating cycle of magnetic saturation; i.e., magnetised, unmagnetised, inversely magnetised, unmagnetised, magnetised, and so forth. This constantly changing field induces an electric current in the second coil, and this output current is measured by a detector. In a magnetically neutral background, the input and output currents match. However, when the core is exposed to a background field, it is more easily saturated in alignment with that field and less easily saturated in opposition to it. Hence the alternating magnetic field, and the induced output current, are out of step with the input current. The extent to which this is the case depends on the strength of the background magnetic field. Often, the current in the output coil is integrated, yielding an output analog voltage proportional to the magnetic field.

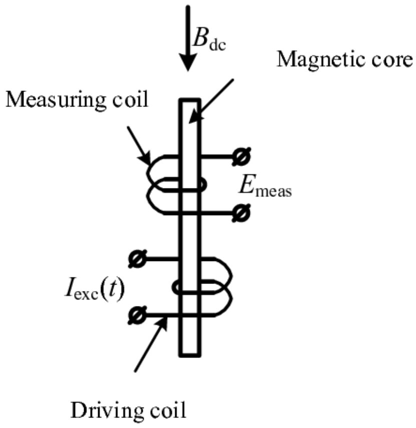

Figure 2.2 *Schematic of single rod fluxgate*

A wide variety of sensors are currently available and used to measure magnetic fields. Fluxgate compasses and gradiometers measure the direction and magnitude of magnetic fields. Fluxgates are affordable, rugged and compact with miniaturization recently advancing to the point of complete sensor solutions in the form of IC chips, including examples from both academia and industry. This, plus their typically low power consumption makes them ideal for a variety of sensing applications. Gradiometers are commonly used for archaeological prospecting and unexploded ordnance (UXO) detection such as the German military's popular Foerster.

The typical fluxgate magnetometer consists of a "sense" (secondary) coil surrounding an inner "drive" (primary) coil that is closely wound around a highly permeable core material, such as mu-metal. An alternating current is applied to the drive winding, which drives the core in a continuous repeating cycle of saturation and unsaturation. To an external field, the core is alternately weakly permeable and highly permeable. The core is often a toroidally wrapped ring or a pair of linear elements whose drive windings are each wound in opposing directions. Such closed flux paths minimise coupling between the drive and sense windings. In the presence of an external magnetic field, with the core in a highly permeable state, such a field is locally attracted or gated (hence the name fluxgate) through the sense winding. When the core is weakly permeable, the external field is less attracted. This continuous gating of the external field in and out of the sense winding induces a signal in the sense winding, whose principal frequency is twice that of the drive frequency, and whose strength and phase orientation vary directly with the external-field magnitude and polarity.

There are additional factors that affect the size of the resultant signal. These factors include the number of turns in the sense winding, magnetic permeability of the core, sensor geometry, and the gated flux rate of change with respect to time.

Phase synchronous detection is used to extract these harmonic signals from the sense winding and convert them into a DC voltage proportional to the external magnetic field. Active current feedback may also be employed, such that the sense winding is driven to counteract the external field. In such cases, the feedback current varies linearly with the external magnetic field and is used as the basis for measurement. This helps to counter inherent non-linearity between the applied external field strength and the flux gated through the sense winding.

2.1.3. Description of Sensys FGM3D TD magnetometer used for the study

The FGM3D TD is a data logging and analysis set for the high performance three-axis magnetic field sensor FGM3D. It combines high quality electronics with easy to use software. This makes it a fundamental measurement set for all scientists and geophysicists in labs, universities or in the field whose work requires precise data of the Earth’s magnetic field.

The hardware allows for simultaneous sampling of 3 channels with a 24 bit digitization and a sample rate of up to 6,300 values per second (6.3 kHz). The device also includes an anti-aliasing filter (as low pass filter Bessel 2nd order) having a cut-off frequency of 3.3 kHz. The connection to the PC is established by an electronically isolated USB 2.0 connection.

Data logging and analysis is carried out by the software that is part of the FGM3D TD. The software includes for example an oscilloscope function having various setting options. Furthermore a spectrum analyser function is included, allowing for analysis of amplitude, noise density spectrum and the magnetic total field.

In addition, different profiles can be created with the software by using xml-files, thus offering flexible configurations. The adjustable CSV recorder for raw data storage completes the functionality of the software.

Figure 2.3 *The Sensys FGM3D TD magnetometer*

2.2. MATLAB code development

A MATLAB code was written to sort, process, plot and analyse the data obtained from the Sensys magnetometer.

2.2.1. About MATLAB, the version used.

MATLAB is a programming platform designed specifically for engineers and scientists. The heart of MATLAB is the MATLAB language, a matrix-based language allowing the most natural expression of computational mathematics.

Using MATLAB, you can:

- Analyse data
- Develop algorithms
- Create models and applications

The language, apps, and built-in math functions enable you to quickly explore multiple approaches to arrive at a solution. MATLAB lets you take your ideas from research to production by deploying to enterprise applications and embedded devices, as well as integrating with Simulink® and Model-Based Design.

Millions of engineers and scientists in industry and academia use MATLAB. You can use MATLAB for a range of applications, including deep learning and machine learning, signal processing and communications, image and video processing, control systems, test and measurement, computational finance, and computational biology.

2.2.2. MATLAB code and description

2.2.2.1.The main program

The program '*Magnetometer.m'* acts as the main command interface which uses switch function to help the user select what process to be done on the data.

Program

```
clc;
clear all;
addpath(genpath('lib'));
disp('1: Convert any character to point in csv file');
disp('2: Convert raw data to daily seconds');
disp('3: Convert sec data to Delta H Corrected');
disp('4: Convert to one min average file');
disp('5: Graphing');

num1=input('Choose the function >');
switch num1
    case 1
    %Convert to point
    char2point();
```

```
case 2
%Convert Data
disp('1: Create daily file');
disp('2: Create a single file');
num2=input('Choose the function >');
    switch num2
        case 1
        %Output Daily file
        raw2dailyfil()
        case 2
        %Output single file
        raw2singlefil()
    end


case 3
%Delta_H
disp('1: Create daily file');
disp('2: Create a single file');
num3=input('Choose the function >');
    switch num3
        case 1
        %Output Daily file
        delH_dailyfil()
        case 2
        %Output single file
        delH_singlefil()
    end

case 4
%One min average file
disp('1: Create daily file');
disp('2: Create a single file using daily file');
num4=input('Choose the function >');
    switch num4
    case 1
        %Output Daily file
        OneMinAvg_dailyfil()
    case 2
        %Output single file
        OneMinAvg_singlefil()
    end

case 5
%Graphing
disp('1: Create daily file');
disp('2: Create a single file');
num5=input('Choose the function >');
    switch num5
    case 1
        %Output daily graph
        graphing_dailyfil()
    case 2
        %Output single graph
        graphing_singlefil()
    end
```

```
end
```

Output

1: Convert any character to point in csv file
2: Convert raw data to daily seconds
3: Convert sec data to Delta H Corrected
4: Convert to one min average file
5: Graphing
Choose the function >

2.2.2.2. To convert a character to decimal point

This program '*char2point.m'* is used to change decimal separator from any character to a decimal point.

Program

```
function char2point()
clear all;
%----Scan input files----------
temp=dir('*.csv');
temp1={temp.name}';
temp2=cell2mat(temp1);
[m1,n1]=size(temp1);
%------Initialise variables-----
k=1;
char = input('Character to be replaced >','s');
while k<=m1
    % Note that the file is overwritten, which is the price for
high speed.

    file      = memmapfile(eval([' temp2(k,:) ']), 'writable',
true );
        char   = uint8(char);
        point   = uint8('.');
        file.Data( transpose( file.Data==char) ) = point;
        %%%delete(file)
    k=k+1;
end
disp('END');
```

2.2.2.3. To convert the raw data to a usable form.

The program *raw2dailyfil.m* and *raw2singlefil.m* are used to convert the data from the instrument to usable form. The programs either writes to separate files for each day or consolidates to a single file respectively.

Program (raw2dailyfil.m)

```
function raw2dailyfil()
clear all;
STN = input('Enter the station name\code(STN) >','s');
%----Scan input files----------
temp=dir('*.csv');
```

```
temp1={temp.name}';
temp2=cell2mat(temp1);
[m1,n1]=size(temp1);
%------Initialise variables-----
time_fin=0;
index1=1;
flag1=0;
tm_start=0;
f=1;
k=1;
while k<=m1
 date_time = fun_importdatetime(eval([' temp2(k,:) ']), 1, 1);
 datetime_char = convertStringsToChars(date_time);
 data=fun_importfile(eval([' temp2(k,:) ']), 15, inf);
 [m2,n2]=size(data);

  %----Execute this only for the first iteration-------
    if flag1==0
        %------extract date & time----------------
        t1=datevec(datetime_char(1:10),'yyyy-mm-dd');
        t2=datestr(t1);
        t3=[t2 datetime_char(11:19)];
        [yy mm dd hh min sec]=datevec(t3);
        tm1=hh+(min/60)+(sec/3600);
        time_fin=tm1;
        tm_start=data(1,1);
        %-----create datenum ref--------------
        startyear=year(t2);
        refdate=[year(t2)-1, 12, 31];
        datenum_ref=datenum(refdate);
        startdaynum=datenum(t2)-datenum_ref;

        %-----create output file--------------
        flag1=1;
        out_fl=[datestr(datenum(t1)) '-' STN '.txt'];
        fid=fopen(out_fl,'w');
    end
     for j=1:m2
        tm2=((data(j,1)-tm_start)/3600000)+time_fin;
        fprintf(fid,'%i    %14.6f    %15.8e    %15.8e    %15.8e
%15.8e\n',startdaynum,(tm2-(index1-
1)*24),(data(j,2)),(data(j,3)),(data(j,4)),(data(j,5)));  %----
write data into file-----

        %-----Construct new file name every 24 hours-----
        if(tm2>(24*index1))
            index1=index1+1;
            fclose(fid);
            f=f+1;
            t4=datenum(t1)+(index1-1);
            t5=datestr(t4);
            %-----yearwise datenum correction--------------
            if(startyear~=year(t5))
               startyear=year(t5);
               refdate=[year(t5)-1, 12, 31];
               datenum_ref=datenum(refdate);
```

```
                startdaynum=datenum(t5)-datenum_ref;
             else
                startdaynum=datenum(t5)-datenum_ref;
             end

             out_fl=[datestr(t4) '-' STN '.txt'];
             fid=fopen(out_fl,'w');
         end
      end
    ime_fin=tm2-(index1-1)*24;
    k=k+1;
end
fclose(fid);
disp('END');
```

Program (raw2singlefil.m)

```
function raw2singlefil()
clear all;
STN = input('Enter the station name\code(STN) >','s');
%----Scan input files----------
temp=dir('*.csv');
temp1={temp.name}';
temp2=cell2mat(temp1);
[m1,n1]=size(temp1);
%------Initialise variables-----
time_fin=0;
index1=1;
flag1=0;
tm_start=0;
f=1;
k=1;
while k<=m1
 date_time = fun_importdatetime(eval([' temp2(k,:) ']), 1, 1);
 datetime_char = convertStringsToChars(date_time);
 data=fun_importfile(eval([' temp2(k,:) ']), 15, inf);
 [m2,n2]=size(data);

  %----Execute this only for the first iteration-------
    if flag1==0
        %------extract date & time---------------
        t1=datevec(datetime_char(1:10),'yyyy-mm-dd');
        t2=datestr(t1);
        t3=[t2 datetime_char(11:19)];
        [yy mm dd hh min sec]=datevec(t3);
        tm1=hh+(min/60)+(sec/3600);
        time_fin=tm1;
        tm_start=data(1,1);
        %-----create datenum ref--------------
        startyear=year(t2);
        refdate=[year(t2)-1, 12, 31];
        datenum_ref=datenum(refdate);
        startdaynum=datenum(t2)-datenum_ref;

        %-----create output file--------------
        flag1=1;
```

```
            date=datestr(datenum(t1));
            out_fl=[date(8:11) '-' STN '.txt'];
            fid=fopen(out_fl,'w');
        end
         for j=1:m2
            tm2=((data(j,1)-tm_start)/3600000)+time_fin;
            fprintf(fid,'%i    %14.6f    %15.8e    %15.8e    %15.8e
    %15.8e\n',startdaynum,(tm2-(index1-
    1)*24),(data(j,2)),(data(j,3)),(data(j,4)),(data(j,5)));  %----
    write data into file-----
        %-----Construct new file name every 24 hours-----
            if(tm2>(24*index1))
                index1=index1+1;
                f=f+1;
                t4=datenum(t1)+(index1-1);
                t5=datestr(t4);
                %-----yearwise datenum correction--------------
                if(startyear~=year(t5))
                   startyear=year(t5);
                   refdate=[year(t5)-1, 12, 31];
                   datenum_ref=datenum(refdate);
                   startdaynum=datenum(t5)-datenum_ref;
                else
                   startdaynum=datenum(t5)-datenum_ref;
                end
         end
        ime_fin=tm2-(index1-1)*24;
        k=k+1;
              end
        end
        fclose(fid);
        disp('END');
```

2.2.2.4. To convert the raw data to a usable form.

The program *delH_dailyfil.m* and *delH_singleyfil.m*are used to subtract the Delta H calculated from the data. The programs either writes to separate files for each day or consolidates to a single file respectively.

Program (*delH_dailyfil.m)*

```
function delH_dailyfil()
clear all;
%----Scan input files----------
temp=dir('*.txt');
temp1={temp.name}';
temp2=cell2mat(temp1);
[m1,n1]=size(temp1);

%Calculate delta_H--------------
f=1;
k=1;
delH=0;
while k<=m1
 data=fun_secfileimport(eval([' temp2(k,:) ']), 1, inf);
 [m2,n2]=size(data);
```

```
    i=0;
    sum=0;
    avg=0;
    for j=1:m2;
    if(1<=data(j,2)<=3)
    i=i+1;
    sum=sum+data(j,(3:6));
    end
    end
    avg=sum(1:4)/i;
    delH=delH+avg(1:4);
    k=k+1;
end
delH=delH/m1;
disp('The value of Delta H');
disp('       x           y        z       total');
disp(delH);

%To write data to file after subtracted delta_H
f=1;
k=1;
while k<=m1
 data=fun_secfileimport(eval([' temp2(k,:) ']), 1, inf);
 [m2,n2]=size(data);

%Day wise file----
        dd=temp2(k,:);
        sz=size(dd);
        titl=dd(1:(sz(2)-4));

        out_fl=[ titl '-DeltaH.txt'];
        fid=fopen(out_fl,'w');

     for j=1:m2

      fprintf(fid,'%i     %14.6f     %15.8e     %15.8e     %15.8e
%15.8e\n',(data(j,1)),(data(j,2)),((data(j,3))-
delH(1)),((data(j,4))-delH(2)),((data(j,5))-
delH(3)),((data(j,6))-delH(4)));  %----write data into file----
-
     end
       fclose(fid);
    k=k+1;
end
disp('END');
```

Program (*delH_singlefil.m)*

```
function delH_singlefil()
clear all;
%----Scan input files----------
temp=dir('*.txt');
temp1={temp.name}';
temp2=cell2mat(temp1);
[m1,n1]=size(temp1);
```

```
%Calculate delta_H--------------
f=1;
k=1;
delH=0;
while k<=m1
 data=fun_secfileimport(eval([' temp2(k,:) ']), 1, inf);
 [m2,n2]=size(data);

    i=0;
    sum=0;
    avg=0;
    for j=1:m2;
    if(1<=data(j,2)<=3)
    i=i+1;
    sum=sum+data(j,(3:6));
    end
    end
    avg=sum(1:4)/i;
    delH=delH+avg(1:4);
    k=k+1;
end
delH=delH/m1;
disp('The value of Delta H');
disp('       x          y         z        total');
disp(delH);

%To write data to file after subtracted delta_H
f=1;
k=1;
dd=temp2(k,:);
sz=size(dd);
if m1==1
titl=dd(1:(sz(2)-4));
out_fl=[titl '-DeltaH.txt'];
else
titl=dd(8:(sz(2)-4));
out_fl=[titl '-DeltaH.txt'];
end
fidt=fopen(out_ft,'w');
while k<=m1
 data=fun_secfileimport(eval([' temp2(k,:) ']), 1, inf);
 [m2,n2]=size(data);

     for j=1:m2
     fprintf(fidt,'%i     %14.6f     %15.8e     %15.8e     %15.8e
%15.8e\n',(data(j,1)),(data(j,2)),((data(j,3))-
delH(1)),((data(j,4))-delH(2)),((data(j,5))-
delH(3)),((data(j,6))-delH(4))); %----write data into file----
-
     end

    k=k+1;
end
  fclose(fidt);
  disp('END');
```

2.2.2.5. To convert the data to one-minute average

The program *OneMinAvg_dailyfil.m* and *OneMinAvg_singlefil.m* are used to calculate the one minute average of the given data. The programs either writes to separate files for each day or consolidates to a single file respectively.

Program (*OneMinAvg_dailyfil.m)*

```
function OneMinAvg_dailyfil()
clear all;
%----Scan input files----------
temp=dir('*.txt');
temp1={temp.name}';
temp2=cell2mat(temp1);
[m1,n1]=size(temp1);
%------Initialise variables-----
f=1;
k=1;
while k<=m1
    data=fun_secfileimport(eval([' temp2(k,:) ']), 1, inf);
    [m2,n2]=size(data);

    %Day wise file----
        dd=temp2(k,:);
        sz=size(dd);
        titl=dd(1:(sz(2)-4));
    out_fl=[titl '-OneMinAvg.txt'];
    fid=fopen(out_fl,'w');

    j=1;
    while (j <= m2 )
        dn=zeros([1 6]);
        i=1;
        while(i<=60 & j<=m2)
            dn=dn(1,:)+data(j,:);
            j=j+1;
            i=i+1;
        end
        dn=dn(1,:)/(i-1);


    fprintf(fid,'%i     %14.6f     %15.8e     %15.8e     %15.8e
%15.8e\n',(dn(1,1)),(dn(1,2)),(dn(1,3)),(dn(1,4)),(dn(1,5)),(dn
(1,6)));
    end
    fclose(fid);
    k=k+1;
end

disp('END');
```

Program (*OneMinAvg_singlefil.m)*

```
function OneMinAvg_singlefil()
clear all;
```

```
%----Scan input files----------
temp=dir('*.txt');
temp1={temp.name}';
temp2=cell2mat(temp1);
[m1,n1]=size(temp1);
%------Initialise variables-----
f=1;
k=1;
%-----creat file----
dd=temp2(k,:);
sz=size(dd);
if m1==1
titl=dd(1:(sz(2)-4));
out_fl=[titl '-OneMinAvg.txt'];
else
titl=dd(8:(sz(2)-4));
out_fl=[titl '-OneMinAvg.txt'];
end
fidt=fopen(out_fl,'w');
while k<=m1
    data=fun_secfileimport(eval([' temp2(k,:) ']), 1, inf);
    [m2,n2]=size(data);

    j=1;
    while (j <= m2 )
        dn=zeros([1 6]);
        i=1;
        while(i<=60 & j<=m2)
            dn=dn(1,:)+data(j,:);
            j=j+1;
            i=i+1;
        end
        dn=dn(1,:)/(i-1);
    fprintf(fidt,'%i     %14.6f     %15.8e     %15.8e     %15.8e
%15.8e\n',(dn(1,1)),(dn(1,2)),(dn(1,3)),(dn(1,4)),(dn(1,5)),(dn
(1,6)));
    end
    k=k+1;
end
fclose(fidt);
disp('END');
```

2.2.2.5. To graph the data

The program *graphing_dailyfil.m* and *graphing_singlefil.m* are used to graph data. The programs either write to separate files for each day or consolidates to a single file respectively.

Program (*graphing_dailyfil.m)*

```
function graphing_dailyfil()
clear all;
axisnum=input('Choose the axis number >');
%----Scan input files----------
temp=dir('*.txt');
```

```
temp1={temp.name}';
temp2=cell2mat(temp1);
[m1,n1]=size(temp1);
%------Initialise variables-----
f=1;
k=1;
while k<=m1
    data=importdata(temp2(k,:));
    doy=data(:,1)+data(:,2)/24;
    h_mf=data(:,axisnum).*10^9;
    %--------------------------


    dd=temp2(k,:);
    sz=size(dd);
    titl=dd(13:(sz(2)-4));
    date=dd(1:11);
    year=dd(8:11);

    figure(1)
    grid on
    plot(doy,h_mf,'*k');
    %Axis limit is set for the x axis-----------
    % axis([356 365 -inf inf])
    %------------------------------------------
    %title(['Average Graph Kannur'])
    title([date ' ' titl])
    %xlabel(['Day of the year 2019'],'fontsize',12,'fontweight','bold','fontname','times');
    xlabel(['Day of the year',' ', year],'fontsize',12,'fontweight','bold','fontname','times');
    ylabel('Magnetic field (nT)','fontsize',12,'fontweight','bold','fontname','times');
    mff2= [date '_' titl '.png'];
    saveas(gcf,mff2);

    k=k+1;
end
disp('END');
```

Program (*graphing_singlefil.m)*

```
function graphing_singlefil()
clear all;
axisnum=input('Choose the axis number >');
%----Scan input files----------
temp=dir('*.txt');
temp1={temp.name}';
temp2=cell2mat(temp1);
[m1,n1]=size(temp1);
%------Initialise variables-----
f=1;
k=1;
while k<=m1
    data=importdata(temp2(k,:));
    doy=data(:,1)+data(:,2)/24;
```

```
    h_mf=data(:,axisnum).*10^9;

    dd=temp2(k,:);
    sz=size(dd);
    if m1==1
    year=dd(1:4);
    titl=dd(5:(sz(2)-4));
    else
    year=dd(8:11);
    titl=dd(13:(sz(2)-4));
    end

    figure(1)
    grid on
    plot(doy,h_mf,'*k');
    %Axis limit is set for the x axis-----------
    % axis([356 365 -inf inf])
    %-------------------------------------------
    title([year ' ' titl])
    xlabel(['Day of the year',' ', year],'fontsize',12,'fontweight','bold','fontname','times');
    ylabel('Magnetic field (nT)','fontsize',12,'fontweight','bold','fontname','times');
    hold on
    mff= [year '_' titl '_total.png'];
    saveas(gcf,mff);

    k=k+1;
end
disp('END');
```

Conclusion

From the above discussion, we understood the working of the magnetometer and successfully developed the MATLAB program for the analysis of the magnetometer data.

Chapter 3
Study of Solar Eclipse using Sensys Magnetometer

3.1. Solar Eclipse on 26th December 2019

An annular solar eclipse occurred on December 26, 2019. A solar eclipse occurs when the Moon passes between Earth and the Sun, thereby totally or partly obscuring the Sun for a viewer on Earth. An annular solar eclipse occurs when the Moon's apparent diameter is smaller than the Sun's, blocking most of the Sun's light and causing the Sun to look like an annulus (ring). An annular eclipse appears as a partial eclipse over a region of the Earth thousands of kilometres wide. The annularity was visible in Saudi Arabia, Qatar, United Arab Emirates, Oman, India, Sri Lanka, Bangladesh, Malaysia, Indonesia, Singapore, Northern Mariana Islands, and Guam. Population centres in the path of the annularity included Kozhikode, Coimbatore, Jaffna, Trincomalee, Sibolga, Tanjung Pinang, Batam, Singapore, Singkawang and Guam. Cities such as Doha, Malappuram, Madurai, Pekanbaru, Dumai, Johor Bahru and Kuching narrowly missed the annular path.

3.2. Study of the Eclipse at Kannur

Raw data obtained from the magnetometer, from 23rd to 28th December 2019 was processed, as the decimal separator was already a point the first part of the code (char2point.m) was not run. The program *raw2singlefil.m* was run and files were generated for each day each having the data corresponding to the same. This was used as the input for the program *delH_dailyfil.m*, which subtracted the average value from 1 am to 3 am such that it subtracted the field due to earth's magnetic field and the magnetospheric contributions where removed from the data. This was, in turn, used as the input for the program *OneMinAvg_dailyfil()*, which calculated the one minute average and reduced the data points to 1440, per day. This was the plotted as shown in figure 3.1.

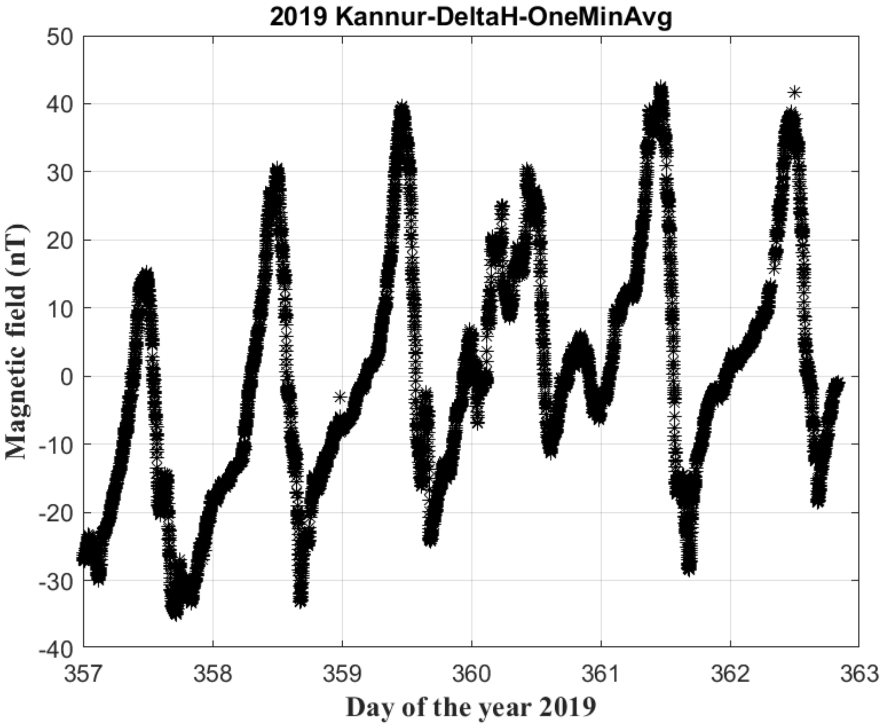

Figure 3.1 *The data plotted from 23rd to 28th December 2019, Kannur*

Now the data from 26th December 2019 was isolated and plotted as this the day corresponding to the eclipse as shown in figure 3.2.

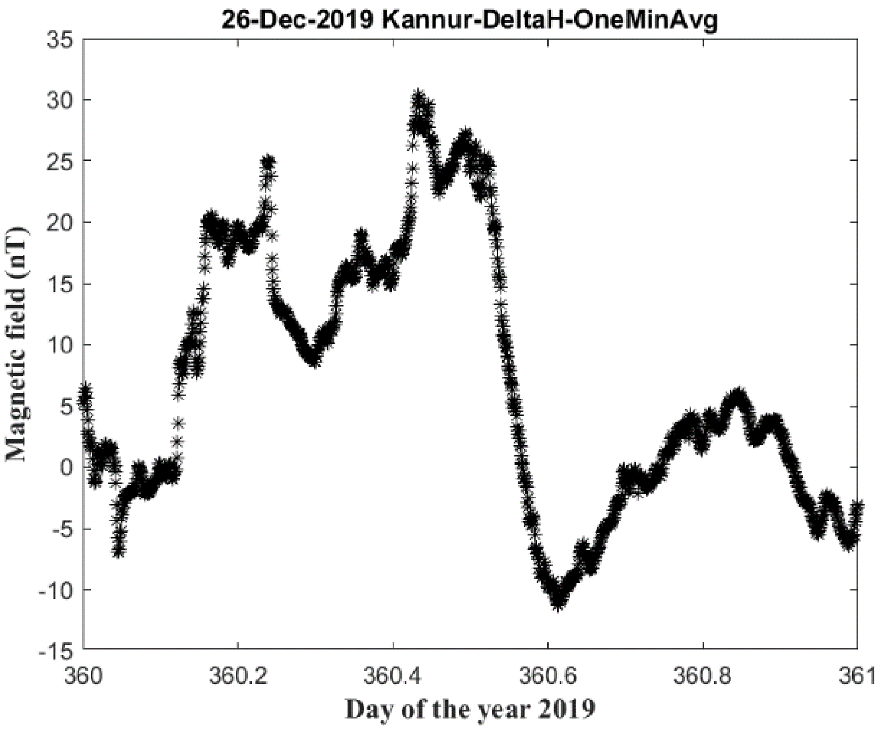

Figure 3.2 *The data plotted for 26th December (Eclipse day), Kannur.*

This can be contrasted with figure 3.3 which shows an average value taken from all the other days which can be used as an estimate for what the plot would have looked is the eclipse did not take place in that day.

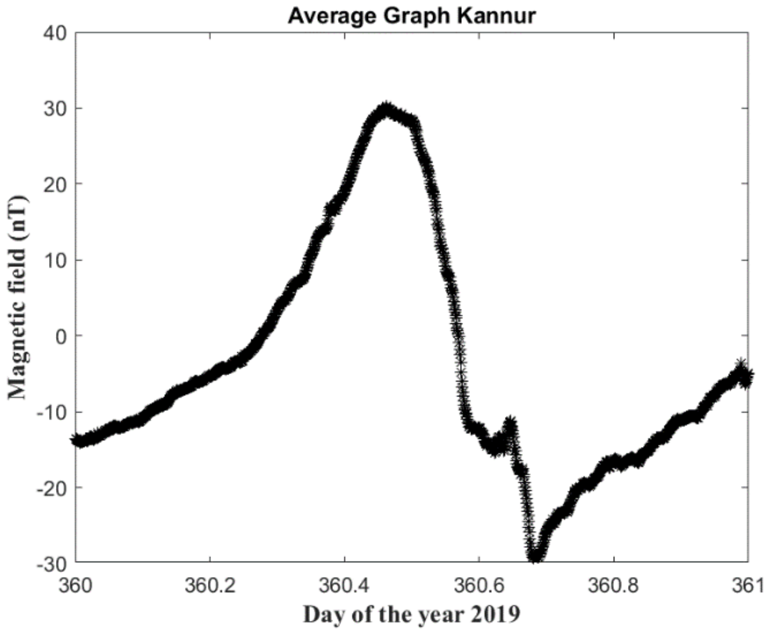

Figure 3.3 *The data plotted from the average value at Kannur.*

Therefore we can conclude that eclipse have had a good effect on the ionospheric magnetic field component at Kannur.

3.3. Study of the Eclipse at Changanassery

Raw data obtained from the magnetometer, from 25th to 30th December 2019 was processed, as the decimal separator was a ‘,’ the first part of the code *char2point.m* was run changing it to ‘.’. The program raw2singlefil.m was now run and files were generated for each day each having the data corresponding to the same. This was used as the input for the program delH_dailyfil.m, which subtracted the average value from 1 am to 3 am such that it subtracted the field due to earth’s magnetic field and the magnetospheric contributions where removed from the data. This was, in turn, used as the input for the program OneMinAvg_dailyfil(), which calculated the one minute average and reduced the data points to 1440, per day. This was the plotted as shown in figure 3.4.

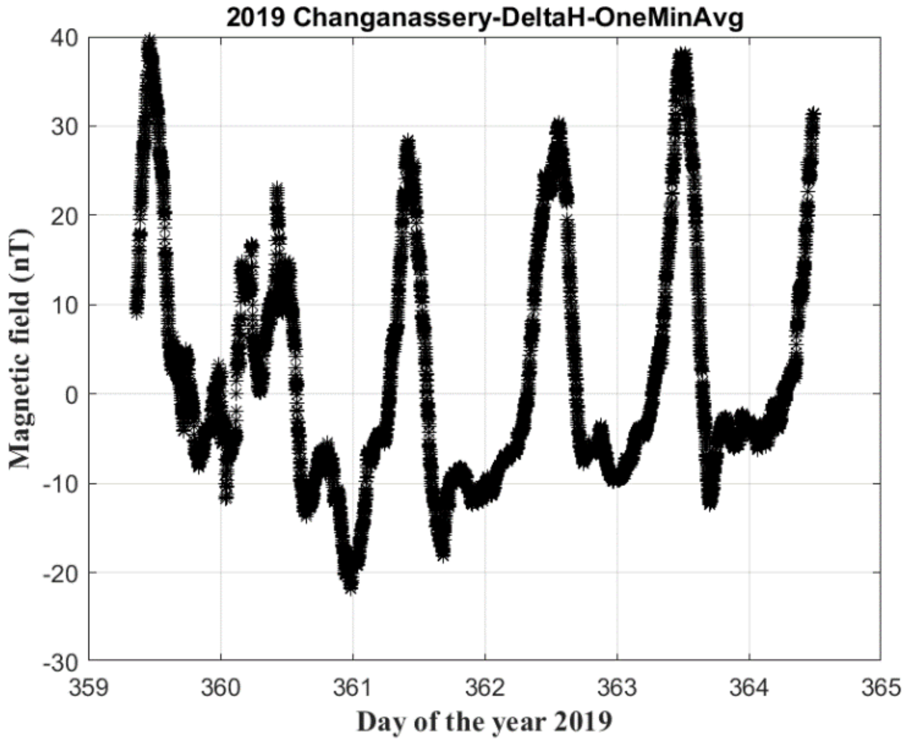

Figure 3.4 *The data plotted from 25th to 30th December 2019, Changanassery*

Now the data from 26th December 2019 was isolated and plotted as this the day corresponding to the eclipse as shown in figure 3.5.

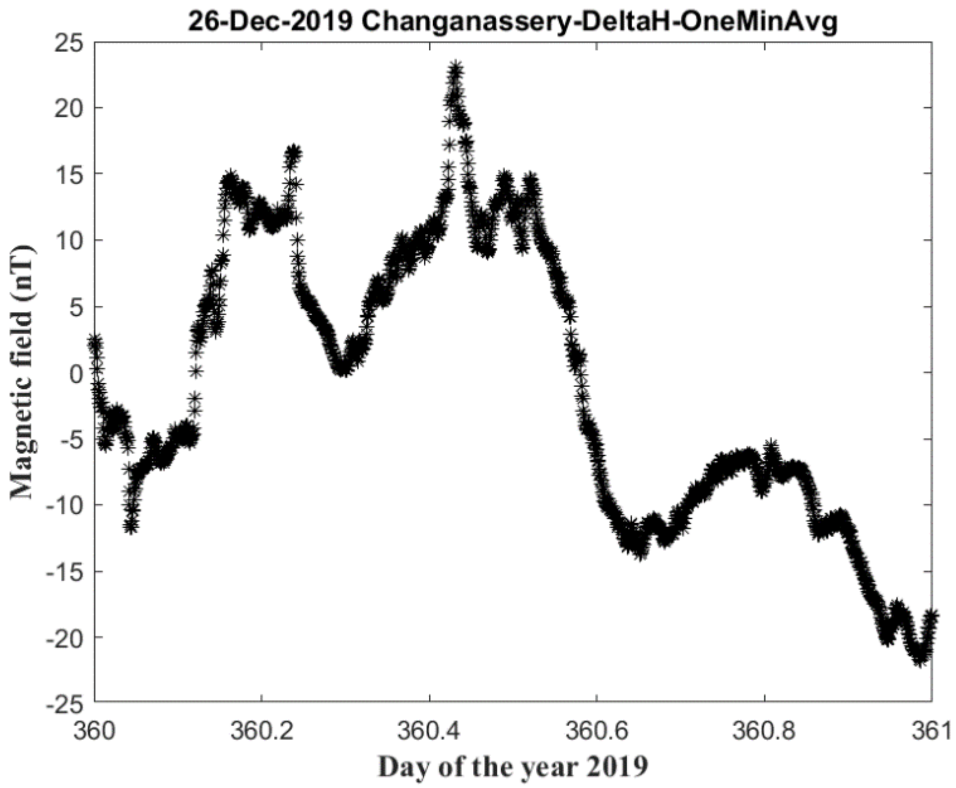

Figure 3.5 *The data plotted for 26th December (Eclipse day), Changanssery*

This can be contrasted with figure 3.6 which shows an average value taken from all the other days which can be used as an estimate for what the plot would have looked is the eclipse did not take place in that day.

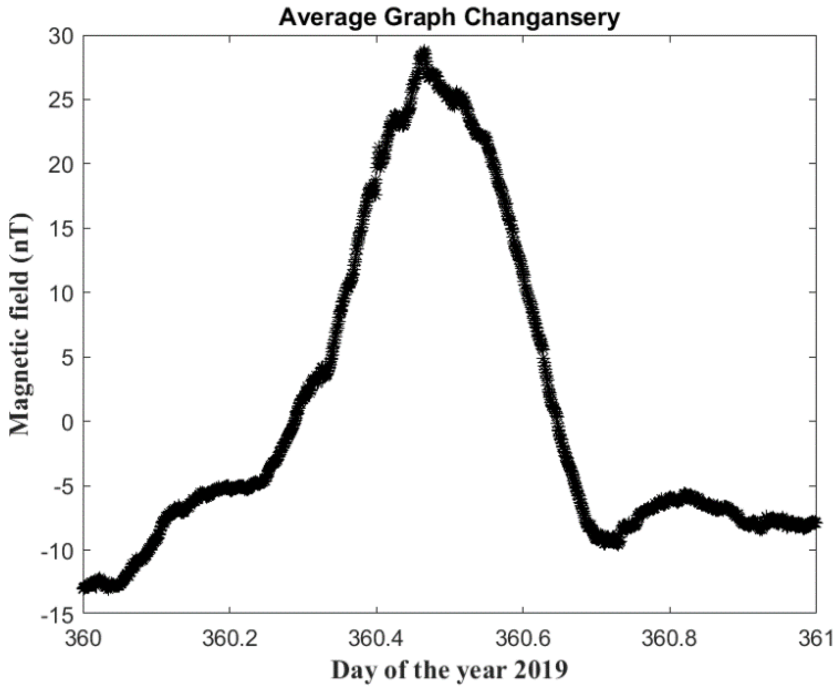

Figure 3.6 *The data plotted from the average value at Changanssery*

Therefore, we can conclude that eclipse have had a good effect on the ionospheric magnetic field component at Kannur.

Conclusion

We understood the various layers of the atmosphere and a detailed study on the ionosphere. We understood how the geomagnetic and magnetosphere contribute to the overall magnetic field at a point. We, in turn, understood the working of magnetometers. The program was developed for the analysis of the data from the FGM3D TD magnetometer and was in turn used to plot the data from the 26^{th} December 2019 Solar Eclipse from Kannur and Changanassery. The effects of the Solar Eclipse in the Ionospheric contribution to the total magnetic field were clearly observed.

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