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SPATIO-TEMPORAL VARIABILITY OF THE HORIZONTAL COMPONENT OF SPACE SOURCE EARTH 0 S MAGNETIC FIELD

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SPATIO-TEMPORAL VARIABILITY OF THE HORIZONTAL COMPONENT OF SPACE SOURCE EARTH'S MAGNETIC FIELD

A THESIS SUBMITTED TO
THE SCHOOL OF GRADUATE STUDIES OF
BAHIR DAR UNIVERSITY



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REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE IN PHYSICS

By

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BAHIR DAR, ETHIOPIA
SEPTEMBER 2019

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Abstract

This study describes equatorial region spatio-temporal variability of space source horizontal component of magnetic field at the surface of the Earth using the data measured from five INTERMAGNET magnetic observatory stations. The space source magnetic field is extracted by subtracting mean of night time magnetic field from the total horizontal component of the Earth's magnetic field. The magnetic field which is mainly originated from the space has a great role in the dynamics of the ionosphere. Measuring magnetic field in the magnetometer is relatively more accurate than measuring electric field and the variation of the field is an indicator for dynamics of the ionosphere. And this can give us a good approximation about dynamics of the ionosphere. The strength of the field is high in between 10.00 hr and 13.00 hr local time. Dip latitudinal variation of day time horizontal component of Earth's magnetic field is more significant than longitudinal variation of the field in equator regions. As we go away from the dip equator the space source magnetic field strength decreases. In AAE station the field strength is maximum (dip latitude 1.8°) followed by MBO (dip latitude 7.65°), GUA (Dip latitude 12.1°), KOU (Dip latitude 16.89°) and API (Dip latitude -29.9°) stations respectively. In AAE It displayed the highest amplitude, while in Apia obtained the lowest. And the space source magnetic field exhibits spatio temporal variation in which the dip latitudinal variation of the space source magnetic field dominates the longitudinal variation of day time magnetic field strength in equator regions. This dramatic increment of the space source magnetic field in AAE in all days, months and seasons could be due to high equatorial electron jet, high conductivity and electric field strength in the dip equator. Unique way of

determining the day time strength of the electron jet is to observe the difference in the magnitudes of the horizontal component of the magnetic field between a magnetometer placed directly on the magnetic equator and one displaced out of it.

Key words: Space source, Magnetic field, Dip latitude, Spatio-temporal

Chapter 1

Introduction

1.1 Background of the study

Solar atmosphere is classified into different regions due to temperature profile and gas density. The sun has a very complex surface magnetic field created by convective flow of electrically conducting material. The expanding wind drags the solar magnetic field outward. The atmosphere of Earth is a layer of gases surrounding the planet Earth that is retained by Earth's gravity. The Earth's ionosphere that covers to an altitude range of approximately 60 km to 1000 km is historically the region of the atmosphere that affects the propagation of radio waves (Brekke, 2013).

The main distinction between the ionosphere region and other regions of the atmosphere is that, it contains more charged particles. The formation of the ionosphere depends on solar radiations such as solar extreme ultraviolet (EUV) and X-ray. The process by which the EUV and X-ray radiation from the Sun interact with neutral atoms giving rise to free electrons is called photoionization. Because of this process, the ionosphere consists of free electrons and ions. The decrease in light intensity and increase in neutral density with decrease in altitude forms an ionization peak in the

ionosphere. However, due to the availability of different atoms and molecules with differing rates of absorption, the ionosphere at all altitudes has a tendency to separate into layers (Kelley, 2009). Since the ionization appears differently at different ionosphere levels, it produces layers or regions which may be identified by their interaction with radio waves.

The ionosphere naturally varies with time of day, season, geographic position and solar activity. To describe the behavior of radio waves in the ionosphere we need to realize that the ionosphere is partially ionized, spherically stratified plasma with irregularities upon which imposed a uniform magnetic field. That is we can treat the ionosphere as plasma embedded in an electromagnetic field (Schunk and Nagy, 2009). The Earth has a magnetic field which is mainly produced within its interior and forms a protecting shield around the planet, called the magnetosphere. The magnetosphere protects Earth's inhabitants from the highly energetic and dangerous particles from the sun and it prevents the Earth's atmosphere from being blown away by the solar wind (Meloni and Lanza, 2006). The observed magnetic field on Earth is called the geomagnetic field. It is a superposition of magnetic fields generated by different sources (Edda Lina Gunnarsdottir, 2012). The field generated by a magnetic dynamo in the Earth's liquid core is called the main field and is by far the most dominant one which are stable in time compared to the external field. The external field is composed of the field produced by the electric currents in the ionosphere and magnetosphere. There is also a magnetic field produced by the induced currents in the crust, mantle and oceans which adds to the total geomagnetic field (Meloni and Lanza, 2006). To summarize, the geomagnetic field components which make up the total geomagnetic field are, the main field and the external fields.

Geomagnetic field measurements and other geological studies showed that the Earth's magnetic field changes significantly with time. The time variations can be from the scale of seconds up to millions of years, they can be periodic or completely random, they can include changes in declination or inclination and the field's total strength can vary from a few nT up to thousands of nT and (Meloni and Lanza, 2006). The time variations are divided into two main groups, long and short term variations. What distinguishes them, apart from the duration, is that long term variations come from the dynamics of the Earth's interior, whereas short term variations have an external origin (Meloni and Lanza, 2006). The long term variations are on a scale of 5 years or more and are called secular variations and (Meloni and Lanza, 2006). The short term variations can be on the scale of seconds or more but their duration hardly exceeds a year. They often cause intense variations in the field and are mainly produced by currents in the magnetosphere and ionosphere. At times, when the intensity and direction of the geomagnetic field vector is constantly changing, the field is said to be magnetically active and periodic variations due to the rotation or orbital motion of the Earth, Sun and Moon are included in the group of short term variations (Jankowski and suksdorff, 1996). The main field variation is originated within the Earth's interior. The Earth's magnetic field is characterized by magnetic field directions of parallel to the Earth's surface at low latitude and perpendicular to the earth's surface at high latitude. Magnetic dip equator (inclination is zero) is the position where the field direction is exactly horizontal.

1.2 Statement of the problem

Earth's magnetic field protects the near-Earth environment from dangerous radiation and high energy plasma from the Sun by partially blocking it out. However, there is always some part of the plasma and radiation that is able to penetrate through the magnetic field barrier, and this often leads to magnetic disturbances around the Earth. In modern times, the need to understand the behavior of the Earth's magnetic field, its origin and variations, is becoming ever more important. With intense research, focused on both the surface of Earth, and the Sun-Earth environment, the goal is to be able to predict the behavior of the magnetic field, just as meteorologists predict the weather (Matzka et al, 2010).

The magnetic field of the Earth is not steady but shows secular (slowly varying) and the other transient (temporal) variations. Transient variations occur very rapidly, within periods of days and are due to external sources probably of solar origin. The regular daily fluctuation in the Earth's magnetic field was first observed by Graham and Stewarts, later it was discovered that these regular daily fluctuations in the geomagnetic field originate from thermally forced motion of conducting air moving over the magnetic field in the ionosphere (Matzka et al, 2010).

The current in the ionosphere can produce a magnetic field and the magnetic field which is mainly originated from the space has a great role in the dynamics of the ionosphere (Matzka et al, 2010). Measuring magnetic field in the magnetometer is relatively more accurate than measuring electric field that has direct role on the dynamics of the ionosphere. And the variation of magnetic field is an indicator for variation of current (or electric field) in the ionosphere and magnetosphere. To know more about the characteristics and dynamics of the ionosphere it is important to study on the parameters that affects the variability of the ionosphere. The current produced by electromotive forces is frequently considered to be due to the action of dynamo, which results in ground perturbation of magnetic field and current. I preferred to study on equatorial region because the equatorial ionospheric dynamics is very complicated and its physical mechanism is not well known. For example it is not yet well known the cause for longitudinal variation of equatorial ionosphere. It may be for example due to EEJ variation. In this study the spatio-temporal variation of the horizontal component of the Earth's magnetic field originated from space source has been investigated by using year 2011 simultaneous data obtained from INTER-MAGNET equator regions. This is not well studied so far, even though which has a great contribution for dynamics of the ionosphere. And the result could be an input for ionospheric dynamics and it can be the base for studies focus on characterization of the ionosphere in the space science. Therefore in this study the spatio-temporal variability of space source Earth's magnetic field which has a great role to know the dynamics of the ionosphere in the space has been investigated.

1.3 Objectives of the study

The intention of this thesis is to investigate the spatial (latitudinal and longitudinal) and temporal variability of horizontal component of space source magnetic field in equatorial regions. And to identify the dominant parameter (latitude or longitude) for the variation of space source day time Earth's magnetic field in equatorial regions and its main cause especially in the noontime.

1.4 Thesis Structure

The over all organization of this thesis is arranged in chapters.

In chapter one the background, statement of the problem and objectives of the thesis are described. Details in ionosphere and magnetic field of the earth was discussed in chapter two. Chapter three covers the methodology used in this thesis. And in the fourth chapter results and discussions are presented. In the last chapter conclusions and recommendations are given.

Chapter 2

Ionosphere and magnetic field of the Earth

2.1 Introduction

The Sun is our nearest star, it is located at an average distance of 1.5×10^8 km from the planet Earth, is a middle aged, main sequence star. According to figure 2.1 the surface of the sun is not solid but a spherical plasmatic gas with radius of about 0.005 AU and has a differential rotational period which increases in latitude from an average value of around 25 days at the equator and around 32 days near the polar region. The Sun is mainly composed of Hydrogen (about 90 percent) and Helium (about 10 percent) with significant amount of other heavy elements. The light of the sun comes from the photosphere, which has a temperature of about 5800 K (Kelvin) (Brekke, 2013). Around this lies a region of hot gas, the chromosphere, and it extends about 10^3 Km from the photosphere. Above that there is a tenuous and even hotter layer, the corona that extends 10^6 Km out into space from the chromosphere. The

visible dark areas of irregular shape of the photosphere that are cooler than the entire solar surface are called sunspots. The sun has a quasi-periodic about 11 year solar cycle.

Approximately every 11 years the Sun moves through a period of fewer and smaller sunspots termed solar minimum, followed by a periodic of larger and more sunspots termed Solar maximum. Sun is a self-luminous ball of gas held together by its own gravity and powered by thermonuclear fusion in its core. From the astrophysical point of view, our Sun is an ordinary star. Compared with most stars, however, the sun is larger, brighter, and more massive. Compared with what we are used to on the earth, moreover, all stars, including the sun have such amazing properties that they are almost beyond our comprehension.

Sun is the only star which is close enough to observe details on its surface such as sunspots, faculae, prominence, coronal holes, flares etc. which are all summarized as solar activity phenomena. The Sun is the driving factor for climate on the Earth and the structure and shape of the Earth's magnetosphere thus determining and influencing the near Earth space environment. Therefore, the study of solar terrestrial relation is great importance for our modern telecommunication systems both based on Earth and in space (Hunsucker and Hargreaves, 2002).

2.2 Physical Characteristics of the sun

The mean distance from the sun to the Earth is called one astronomical unit and it is about 1.5×10^8 km. The solar radius or the radius of visible disc (Sun's radius) is 7×10^8 m. Since the speed of light(c) is close to 3×10^8 m/s, it will take the light about 500 seconds or 8 minutes to pass from the sun to the Earth (Charles, 2017). The

sun's mass is close to 2×10^{30} kg which is about 98 percent of the solar systems mass. Sun does not rotate as a rigid sphere. The equator of the Sun rotates faster than the poles of the Sun as seen from figure 2.1. This is called the differential rotation. Sunspots and many other solar activities are due to this differential rotation.

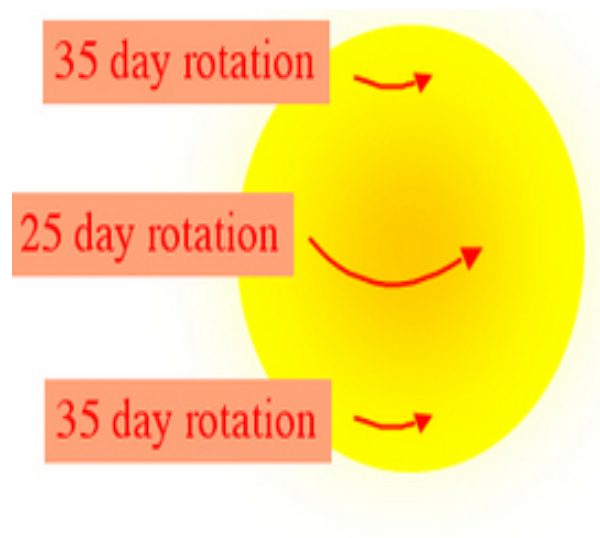


Figure 2.1: Differential rotation of the sun ([http://astronomy.swin.edu.au /cosmos /D/ Differential + Rotation](http://astronomy.swin.edu.au/cosmos/D/Differential+Rotation)).

2.3 The interior part of the sun

As we have seen from figure 2.2 the sun's interior part consists, the core, the radiative zone, and the convection zone.

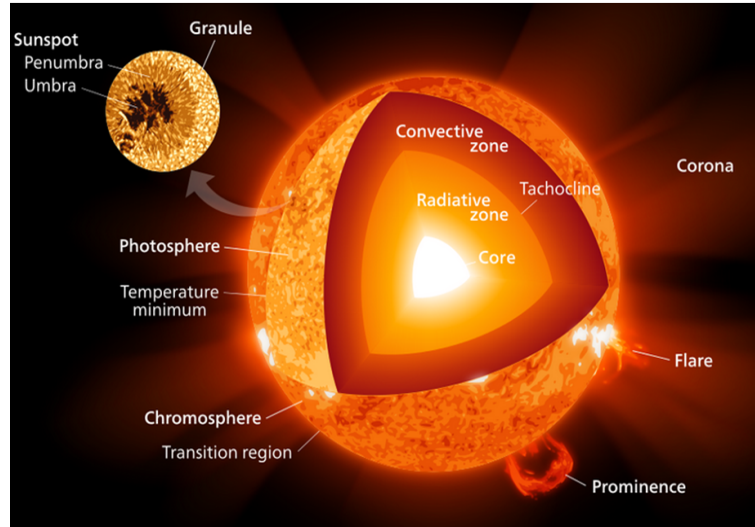


Figure 2.2: The interior part of the sun (https://en.wikipedia.org/wiki/File:Sun_poster.svg).

2.3.1 The Core

The core of the sun extends to 0.25 times the radius of the sun. It has a temperature of 1.5×10^7 kelvin and density $1.6 \times 10^5 \text{ kg/m}^3$. The solar nuclear energy is produced here. The source of all energy radiated by the Sun lies in its core, a central region comprising only 1.5 percent of the total solar volume. This is a very large thermonuclear reactor where Hydrogen atoms are fused together to form Helium, releasing energy at the rate of 3.86×10^{26} Joules per second. The fusion reactions in the solar core take place because of the very high temperatures and very large pressures present in this region of the Sun. Although there is no way of measuring these quantities directly, physical models of the Sun suggest that the core temperature is around 15 million degree kelvin and the central pressure is about 250 billion atmospheres (250 billion times the pressure on the Earth at sea level). It is the gravity of the Sun

that compresses the core to such a high pressure and resultant high temperature, which then is sufficient to ignite the fusion reactions that take place (Charles, 2017). The overall result is to convert four Hydrogen atoms into one Helium atom (Charles, 2017). There are two distinct reactions in which 4 H atoms may eventually result in 1 He atom. The reaction can be summarized as follows.

$$^1H_1 + ^1H_1 \rightarrow ^2H_1 \rightarrow e^+ + \nu + 0.42MeV,$$

$$^1H + ^2H \rightarrow ^3He_2 + \gamma + 5.5MeV,$$

$$^3He_2 + ^3He_2 \rightarrow ^4He_2 + 2^1H_1 + 12.8MeV,$$

where e^+ , ν and γ represent a positron, a neutrino and a gamma ray quantity respectively. We notice four protons are converted into one helium nucleus while an energy is released (Brekke, 2013).

2.3.2 Radiative zone

The radiation zone extends between 0.25 and 0.7 radius of the sun. It has less temperature and density than the core. Energy is transported by radiation and particles in this zone. The energy generated at the core which is mostly in the form of high frequency x-rays and gamma rays flows out into the next spherical layer which is called the radiative layer. It is quite a broad layer extending from the core boundary to almost 71 percent of the sun's radius. Moving with the velocity of light, the out flowing energy is expected to cross the radiative layer fast but on account of multiple deflections, absorption, re radiation, etc., in the radiative layer, the actual movement is very slow and it may take millions of years in some cases for radiation to work its way up to the top surface. The temperature drops from the core outward as the heat energy expands into an ever increasing volume from a value of about 15. million K

at the core to about 2.5 million Kelvin at the top of the radiative layer.

2.3.3 Convection zone

The convection zone has less density and temperature than the other two regions. Energy is transported through convection by actual motion of particles, in this region. By the time, the outgoing radiation reaches the top of the radiative layer, the solar atmosphere becomes somewhat opaque to the outgoing radiation with the consequence that the heat energy piles up in a narrow transition zone at the top of the radiative layer causing the material below to be extremely hot as compared to that above. Across the convective layer, the temperature drops enormously from a value of about 2 million Kelvin at the bottom to about 6,000 Kelvin at the top and the outer layer of the sun, energy is transferred outwardly by convection.

2.4 The Solar Atmosphere

The outer layers of the sun are the only ones that emit radiation that reaches us here on the Earth. Light from deeper layers is absorbed by overlying gases before the light can emerge from the sun. The deepest layer that we can see is the photosphere. Above the photosphere is the chromosphere and then the corona, which extends into interplanetary space to form the solar wind. The solar atmosphere extends from the photosphere to very large heliocentric distances (Jursa, 1985). Based on the temperature or density profile the solar atmosphere can be divided into three regions. These are Photosphere, Chromosphere, Corona Which are described below.

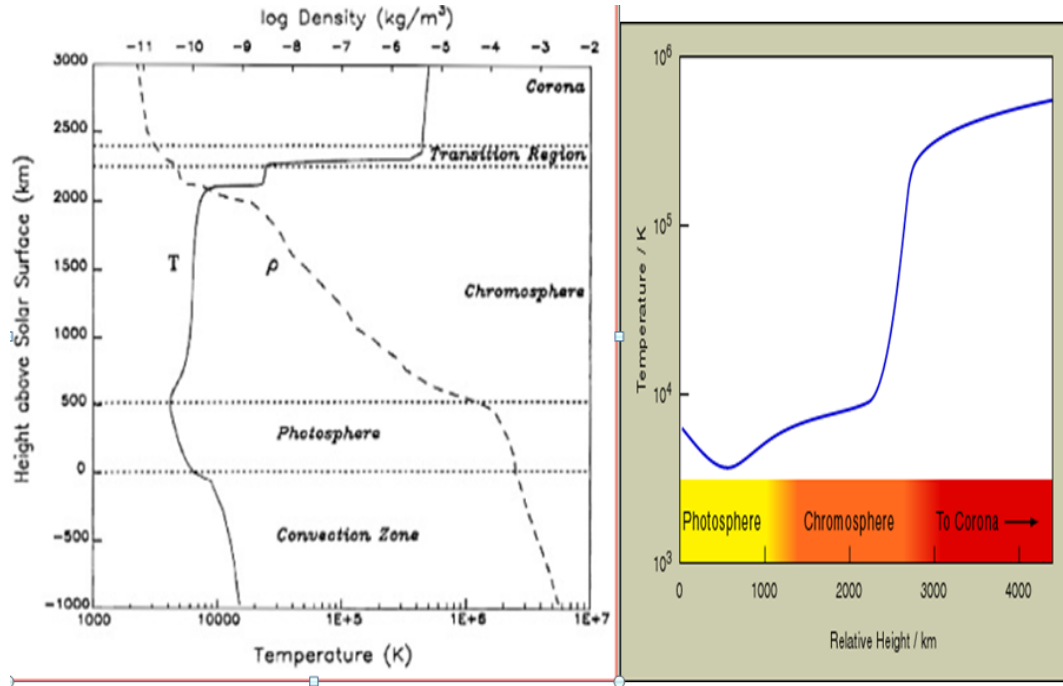


Figure 2.3: The temperature and density profile of solar atmosphere (Brekke, 2013).

2.4.1 Photosphere

Photosphere exists above the convective layer. The temperature decreases from 6400 to 4200 K and it is about 500 km thick (Brekke, 2013). Like solar interior it consists of mostly hydrogen and helium, except there exists some gases in neutral form. It is the place where sunspots are found which have lower temperature than the surrounding area. Sunspots can be used to determine the rotation period of the sun. Observations of spots on the solar surface were reported by ancient Chinese, Japanese, and Greek literatures. However, Galileo Galilei was the first to observe sunspots using telescope. He realized that spots were markings on the visible surface of the sun that they moved as the sun rotated.

2.4.2 Chromosphere

The chromosphere is a layer above the photosphere. The chromosphere which is about 1000 km thick. The temperature of the sun rises to about 10,000 Kelvin in the chromosphere. Spectroscopic examination has shown that the color of the chromosphere is caused by strong hydrogen emission, thereby demonstrating the presence of hot hydrogen in the layer. The chromosphere lies between the corona and the photosphere and can be observed during short phases of solar eclipses, briefly just after the sun's bright photosphere is completely blocked by the moon (during a total solar eclipse). Above the photosphere the temperature passes through a minimum of 4000 Kelvin and then rises to several 10^4 kelvin in the chromosphere and much more rapidly in the transition region until the coronal temperature (10^6 kelvin) is reached.

2.4.3 Corona

The corona is the outer most layer of the solar atmosphere. It is visible part of the sun as a white crown surrounding the sun and its shape is strongly dependent on the solar activity cycle (Koskinen, 2011). The corona varies from 2000 to 3000 km up to several solar radius. Like the rest of the sun, the corona is made up of mostly of hydrogen with a small amount of helium traces of heavier elements. The temperature varies from 1 to 2×10^6 Kelvin. From this region EUV, X-ray, and radio emissions are originating. And the coronal magnetic field affects the density distribution and dynamics of this region in a very different ways. The radiation intensity in this region is highly variable with respect to space and active region with unusually high radiation intensity. The corona intensity of light cannot be seen with the naked eye. Temperature is firmly uniform due to this solar magnetic field is dipolar, and solar

atmosphere is fully ionized. Then thermal conductivity is very high here, because Hydrogen and Helium are almost totally ionized. The high temperature of the corona apparently is maintained through heating by magnetic fields (Jursa, 1985).

2.4.4 The Transition Region

At the top of the chromosphere temperature rapidly increases from about 10^4 Kelvin to over 10^6 Kelvin. This sharp increase takes place within a narrow region called the transition region.

2.5 Solar wind

Solar wind is a flow of ionized plasma and solar magnetic field that provides interplanetary space. It is the result of huge difference in gas pressure; this pressure difference drives the plasma out ward. According to figure 2.4 the solar wind is significantly influenced by solar activity and interact with the magnetic field of the Earth. It consists largely of ionized hydrogen, ionized helium still fewer ions of heavier elements. The quiet sun does not only radiate electromagnetic waves in the frequency range from a few nanometers to a few hundred meters, but also particles. This wind is not a steady wind, but varies quite strongly in velocity as well as density at a distance from the sun corresponding to the Earth's orbit. During the quiet condition the wind has a medium velocity of 400 km/s and can however, vary between 200 and 700 km/s . The wind contains plasma with very high thermal energy and magnetic field with it.

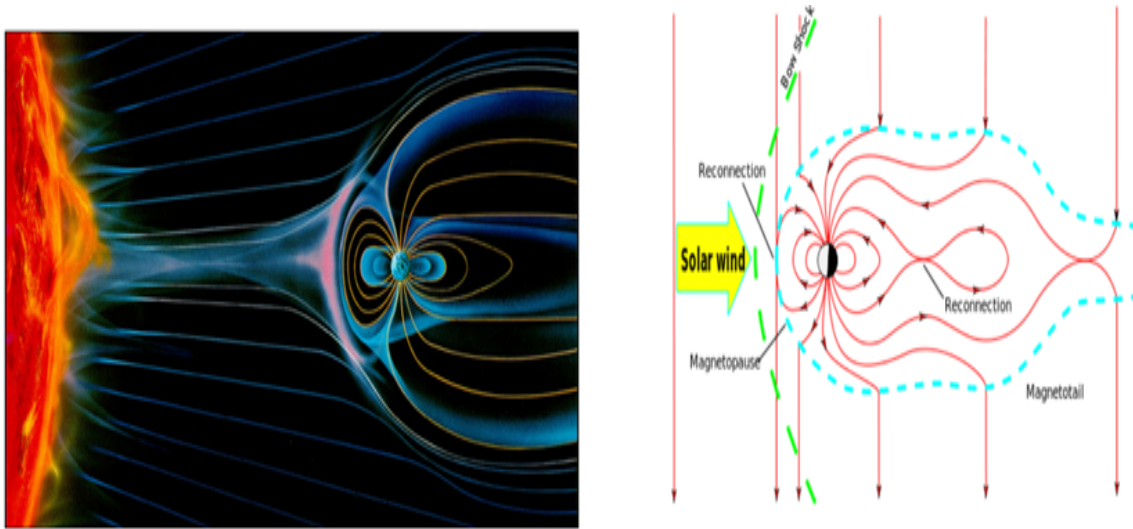


Figure 2.4: The interactions of the solar wind and the magnetosphere of the Earth (Auster, 2008).

2.6 Ionosphere and the Earth's Neutral atmosphere

Atmosphere of the Earth can be broadly categorized in to neutral atmosphere and charged atmosphere based on it's composition. The different temperature profiles of the atmosphere can also be used to classify Earth' s atmosphere as well.

2.6.1 Neutral Atmosphere

Based on temperature profile and the height at which they are situated, neutral atmosphere is divided in to troposphere, stratosphere, mesosphere and thermosphere. Based on figure 2.5 in the troposphere the atmospheric temperature initially decreases with altitude from the ground surface temperature 290 kelvin to nearly 215 kelvin at tropopause which is about 10 km height above the ground (Aurons, 1985). And the Stratosphere, where ozone layer is found begins with increasing temperature up

to 280 kelvin at about 50 km due to partly absorption of ultraviolet solar radiation by Ozone layer (Aarons, 1985). The Mesosphere is the coldest sphere, mesosphere is emerged because of radiative cooling created and a very sharp temperature decrease is happened to a minimum value which ranges between 130 kelvin - 190 Kelvin at about 90 km (Aurons, 1985). Above the mesopause is the thermosphere, temperature is increased dramatically due to absorption of higher energy solar photons, ultraviolet (UV) and extremely ultraviolet (EUV) radiation from the sun which forms high degree of ionization. This increase in temperature might be above 1000 Kelvin (Aurons, 1985).

2.7 Thermal Structure of the Earth's Atmosphere

An atmosphere is the gaseous envelope around a celestial body. Important factors controlling the state of an atmosphere are gravity, temperature and composition (Brekke, 1997).

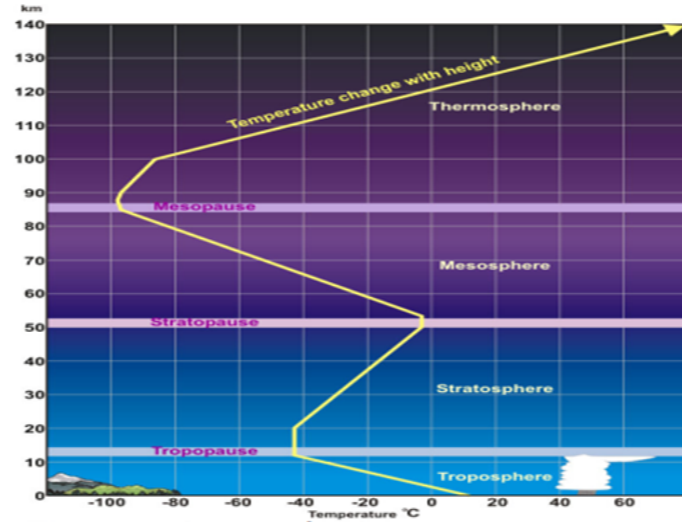


Figure 2.5: Schematic atmospheric temperature profile (Fayose et al , 2012).

2.8 Charged Atmosphere

Higher the altitude the number density of ions and electrons is increased appreciably due to mainly photoionization especially at the equatorial regions, so this causes the decrease in the number density of neutrals at higher altitudes (Das Gupta, 2007). Ionosphere is highly conducting ionized portion of the upper atmosphere. It extends from about 60 km to 1000 km in altitude and completely encircles the Earth (Schunk and Nagy, 2000). The ionosphere exists because of the radiations emitted by the Sun (Schunk and Nagy, 2009). The temperature of ionosphere increases rapidly with increasing altitude up to about 200 km, followed by a leveling off in the 300 to 500 km region. This heating is the result of photoionization and photo dissociation of molecules into atoms and ions by direct absorption of solar photons. The ionosphere is initially ionized by the solar radiation, so its major constituents are charged ions

and freely moving electrons (Rajesh Tiwari et al, 2009). Different ionospheric effects have been seen seasonally and diurnally due to different solar activities such as solar maximum which is related to solar flares and coronal mass ejection which cause intense disturbance to the magnetosphere of the Earth temporally. Solar photons such as EUV, and x ray radiation which have sufficient energy to ionize the neutral thermosphere are responsible for the production of ionosphere (Aurons, 1985). Moreover, energetic particle precipitation has a great significance in ionizing the neutral atmosphere at higher latitude (polar and aurora regions). The amount of ionization that is present is determined by the balance of the source or production of the ions (photoionization) with the loss (recombination) of the ions. The density of the ionized gas in the ionosphere and the frequency of the electromagnetic wave which propagates through determine the amplitude of bending angle (refraction angle)(Cummer et al, 2000).

2.9 Formation of the ionosphere

The main distinction between the ionospheric region and other regions of the atmosphere is that it contains more charged particles. The formation of the ionosphere depends on solar radiation such as, solar extreme ultraviolet(EUV)and X-ray. The photo and impact ionization are described in figure 2.6. The process by which the EUV and X-ray radiation from the sun interact with neutral atoms giving rise to free electrons is called photoionization. Because of this process, the ionosphere consists of free electrons and ions.

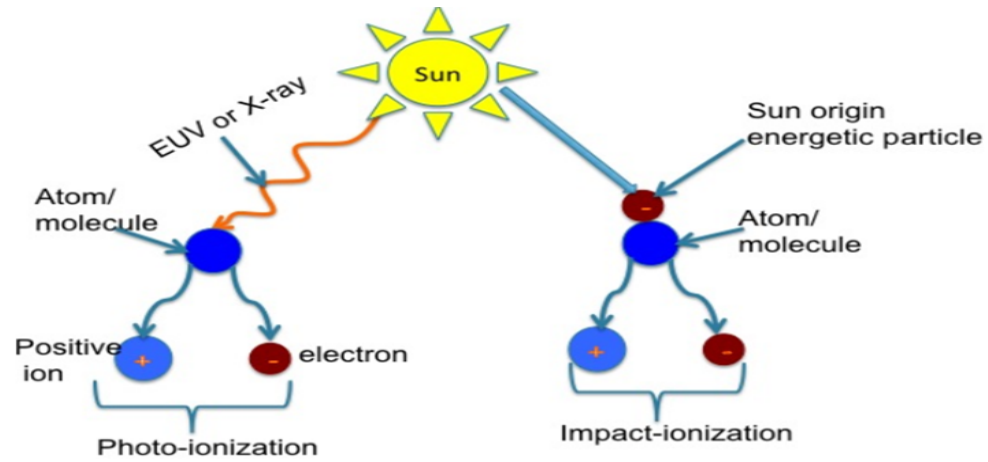


Figure 2.6: Schematics of photoionization (left) and impact ionization (right), adopted from Nigussie, (2013).

Figure 2.7 can show as the altitude profile of ion production will have a peak at some altitude because the rate of the ionization depends on neutral density (that decrease with height) incoming solar-radiation intensity (that increase with height). Solar irradiation of intensity I decrease due to absorption downward in the Earth's atmosphere where the neutral density increases toward the Earth. A maximum ionization rate therefore occurs at some altitude.

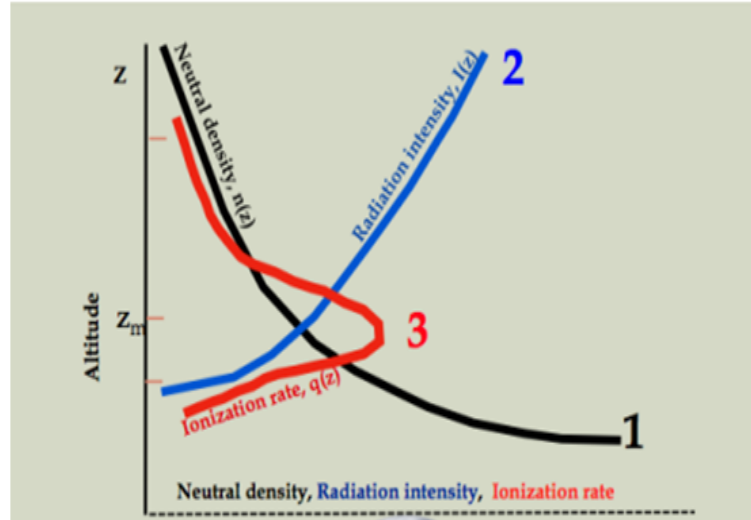


Figure 2.7: Solar irradiation intensity, neutral density and ionization rate (brekke, 2013).

2.10 Regions of Ionosphere

Ionosphere forms different regions which are characterized by electron number density that they contain. These regions are: D-region, E-region and F-region (F_1 and F_2 regions) at various altitudes above the surface of the Earth. Each region is characterized by a local maximum in the number density of ions.

D region: 60 Km up to 90 km, $n_e = 10^8$ up to $10^{10} m^{-3}$

E region: 90 Km up to 150 km, $n_e = 10^{10}$ up to $10^{11} m^{-3}$

F region: 150 Km up to 1000 km, $n_e = 10^{11}$ up to $10^{12} m^{-3}$

The D region

The lowest ionospheric region which extends from approximately 60 km to 90 km at which, Recombination is high. The peak electron density in the D-region is about

10^{10} electrons per cubic meter. The main sources of ionization in the D-region are solar UV photons ionizing nitric oxide (NO) and ionization here can be due to strong ultraviolet emission, at a wavelength of 121.5 nm. In the D-regions, chemical processes are the most important, molecular ions dominate, and N_2 , O_2 , and O are the most abundant neutral species and ions NO^+ and O^{2+} (Schunk and Nagy, 2009)

The E region

It extends from 90 to 150 km and the peak electron density in the E-region is over 100 times greater than the peak density in the D-region. E-region is formed by both low energy X-rays and far UV and besides solar photons, E-region ionization also occurs due to energetic particles precipitating into the atmosphere and by impact ionization (Schunk and Nagy, 2009). In the E-regions N_2 , O_2 , and O are the most abundant neutral species and NO^+ , O^{2+} , and N^{2+} are the most molecular ions which dominate the region.

The F region

It is the most dense region of the ionosphere which ranges from 150 km up to 1000 km and usually peaks at 350 km. The F- region is formed by extreme UV (EUV) solar radiation. Ionizing atomic oxygen which dominates the F-region. The F-region divides into two regions namely F_1 and F_2 regions during the day because of the enhanced photo ionization at high altitudes (Figure 2.8). The F_2 peak is more denser than the F_1 peak which disappears during night time. In these regions, the atomic species (O^+ and O) dominate. The peak ion density in the F_2 region is $10^6 m^{-3}$ (Schunk and Nagy, 2009).

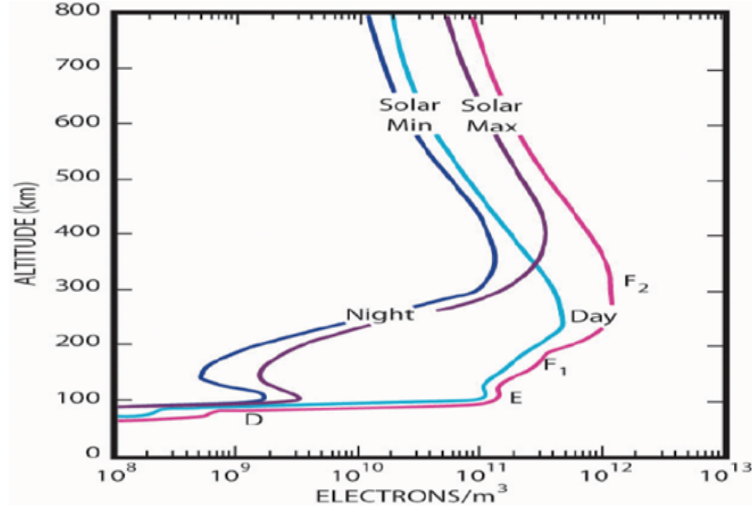


Figure 2.8: Ionospheric electron density profile and regions of ionosphere from Fayose et al, (2012).

2.11 Characteristics of the Equatorial Ionosphere

The interaction of the charged particle with the geomagnetic field is of particular interest near the magnetic equator, where the Earth's magnetic lines of force are nearly horizontal, and the Earth's atmosphere is most exposed to Sun's ionizing radiation, lead to various geomagnetic and ionospheric phenomena, many of which are unique to the region (Kelley, 2009). The location of the geomagnetic equator (or dip equator) is usually described as the locus of zero dip along the surface of the Earth. The characteristics of the equatorial ionosphere is markedly different from the ionosphere encountered at other magnetic latitudes. By virtue of Lorentz force, the charged particles move readily along the magnetic lines than across them. In the equatorial ionosphere there are often pronounced horizontal gradients of electron density, and horizontal plasma motions play greater part in shaping the ionosphere.

The geomagnetic field (flux density B) points horizontally and essentially northward at equatorial latitudes, so a west-to-east electric field E_x produces upward plasma drift. The equatorial ionosphere is unique in many ways. Global scale dynamo action, i.e., generation of currents by electromotive forces due to tidal winds, results in the generation of planetary scale east-west electric fields at low latitudes around the dip equator (Kelley, 2009). Above the magnetic equator, the geomagnetic field lines are horizontal to the Earth's surface, which result in different geophysical phenomena peculiar to the equatorial region. They are: Equatorial Electro jet (EEJ), Equatorial Ionization Anomaly (EIA), generation of plasma irregularities, Pre-Reversal Enhancement (PRE), etc.

2.11.1 The Equatorial Electro jet (EEJ)

The most important dynamo effect at the low latitude is the daily variation of the atmospheric motion caused by the tides of the atmosphere, i.e., the diurnal and semi-diurnal oscillations, which are excited by the heating of the atmosphere due to solar radiation. The current system created by this tidal motion of the atmosphere is called solar quiet or Sq current (Kelley, 2009). This current system creates daily magnetic field variations, records of which are obtained at many different magnetic observatories distributed across the globe. These recordings can be used to construct the Sq current system. Due to the special geometry of global scale dynamo electric field E in the east west direction and the geomagnetic field B in the north south direction over the magnetic equator, electrons drift vertically with respect to ions and due to limitation of vertical extent of dynamo E-region, a vertical polarization electric field sets up. This vertical polarization electric field results in the enhanced conductivity in the

eastward direction. This large current is known as the Equatorial Electro jet (EEJ) (Agbo et al, 2017). Since the magnetic field lines in the equatorial ionosphere are directed northward and parallel to the Earth's surface, the eastward ionospheric electric field drives an eastward Pedersen current and the Hall current, which flows vertically downward at the equator (Agbo et al, 2017). It is the cause for charge separation in the equatorial ionosphere with negative charges accumulating on the top boundary and positive charges accumulating at the bottom of the highly conducting layer. This space charge distribution creates a secondary polarization electric field, directed vertically upward. The polarization electric field drives a vertical Pedersen current opposing the Hall current until it compensates it. Since the Hall conductivity is typically about four times higher than the Pedersen conductivity, the polarization field must also be four times stronger than the primary electric field. Moreover, the polarization electric field generates a secondary Hall current component flowing eastward, about 16 times stronger than the primary eastward Pedersen current, this explaining the amplification (enhancement) of the equatorial electro jet current above the equator (Agbo et al, 2017). In regions around the magnetic dip equator makes the phenomenon an intriguing and fascinating one. The study of the EEJ began with the establishment of geomagnetic observatory at Huancayo, Peru in 1992 with the desire to understand the abnormal solar daily variations of the horizontal component H of the geomagnetic field at an equatorial station. The EEJ leads to many interesting phenomena in the equatorial and low latitude ionosphere (Teshome, 2011). Figure 2.9 described that the stronger EEJ region is from -3° to 3° from the dip equator. The ionosphere carries electric currents, because, winds and electric fields drive ions

and electrons in different directions. Let N be the ion or electron density, ν the collision frequency with neutral particles and ω the cyclotron gyro frequency ($\omega = e\mathbf{B}/m$), where e is electronic charge and m is particle mass). The direct or longitudinal conductivity (σ_o) is the conductivity parallel to the geomagnetic field $\mathbf{B}$. The Pedersen or transverse conductivity σ_1 or σ_p is the conductivity parallel to electric field $\mathbf{E}$ and perpendicular to $\mathbf{B}$ and the Hall conductivity σ_2 or σ_p is the conductivity perpendicular to both $\mathbf{E}$ and $\mathbf{B}$. At the dip equator region shown in figure 2.9 a strong vertical polarization field exists which greatly enhances the direct conductivity.

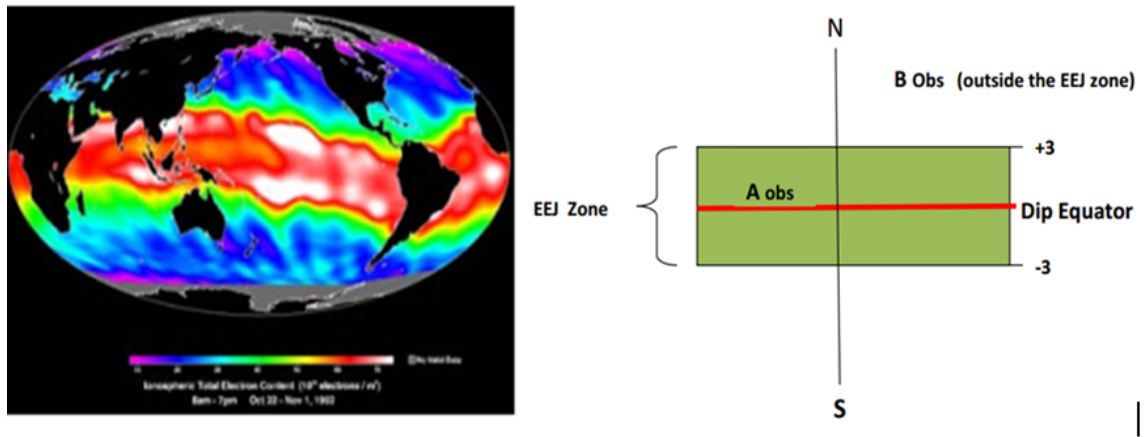


Figure 2.9: Region of dip equator and equatorial electro jet (Agbo et al, 2017).

2.11.2 Equatorial Ionization Anomaly (EIA)

Near the geomagnetic equator, the horizontal magnetic field together with west east electric field, produce vertical plasma drift. This $\mathbf{E} \times \mathbf{B}$ drift is upward during the day and, when combined with preferential diffusion along the direction of the magnetic field, leads to an interesting phenomenon, called the Equatorial Ionization Anomaly

(EIA) (Agbo et al, 2017). This Appleton anomaly is caused by a fountain effect of uprising plasma, occurring in the evening and pre-midnight hours, giving rise to enhanced plasma density about 15° north and south of the magnetic dip equator. Interesting magnetic signatures in the F-region are produced by pressure and gravity driven currents and by plasma instabilities and cavities ("plasma bubbles").

2.11.3 The Ionospheric Disturbances

Ionospheric disturbances can result from solar disturbances or geomagnetic field disturbances. The ionospheric disturbances are associated directly or indirectly with the events on the sun. The geomagnetic disturbances are also caused by events initiated from the sun; however, these events rather affect the outermost geomagnetic field line (also called the magnetopause) and compress the geomagnetic field (Schunk and Nagy, 2009).

2.11.4 Ionospheric storms

The ionosphere suffers major perturbations called storms. They last from a few hours to a few days and tend to occur during disturbance resulting from increases in solar activity communicated via the solar wind. Three phases are identified in ionospheric storm. The first is initial or positive phase, associated with an increase in electron density from the normal value and usually lasts for a few hours. Then follows the main or negative phase when the electron density is reduced below normal values. The final phase is the recovery phase in which the ionosphere gradually returns to normal over a period of one to several days (Hunsucker and Hargreaves, 2002).

2.11.5 Geomagnetic storms

Geomagnetic storms usually occur in conjunction with ionospheric storms and can be caused by solar flares, high speed solar wind streams. The storms are usually associated with increased electron densities in the lower ionosphere and a simultaneous increase in absorption of radio waves. Like the ionospheric storm, it may last from a few hours to several days. (Hunsucker and Hargreaves, 2002). Because magnetic storms can be monitored without great difficulty using a magnetometer, and long runs of such measurements exist, the magnetic storm has come to be a common reference point in geophysical studies (Hunsucker and Hargreaves, 2002).

2.12 Variations of the ionosphere

Any change in the activities of the Sun including spatial variation with respect to the Earth can bring about changes in the ionosphere. The ionosphere is not a stable medium that allows the use of the same frequency throughout the year, or even over 24 hours. The ionosphere naturally varies with time of day, season and geographic position. The variations are generally classified into two types:- 1) Regular variations which occur in cycles and therefore can be predicted in advance and 2) Irregular variations which occur due to abnormal behavior of the Sun and cannot be predicted in advance. The major variation are described as follows.

2.12.1 Diurnal variation

Diurnal variation is due to the coming and going of the ionization sources from the sun over the sky that is the day and night electron density of the ionosphere is

not the same. Night time electron densities are much lower than day time electron density because in night time the recombination rates are higher in the absence of ionization sources. The day time electron density reaches its peak value at noon hours. The main constituents of the ionosphere are neutral atoms and molecules. However, the charged nature of the ionosphere is due to the production of electrons and ions primarily by solar ultraviolet radiation from the sun. This again means that the ionosphere is produced during the day and is reduced during the night due to recombination processes of electrons and ions. Ionization depends primarily on the Sun and its activity. The amount of ionization in the ionosphere varies greatly with the amount of radiation received from the Sun (Kelley, 2009).

2.12.2 Seasonal variation

Seasonal variation is due to Sun-Earth geometry variation. The ionosphere exhibits strong seasonal and solar cycle variations because the main source of ionization and energy for the ionosphere is photo-ionization. Therefore, whenever there is a change in solar zenith angle or the solar radiation fluxes, the ionosphere will change. The ionospheres seasonal variation is related to a solar zenith angle change, while its solar cycle variation is related to a change in the solar EUV and X-ray radiation fluxes. (Kelley, 2009).

2.12.3 Latitudinal variations

Latitudinal variation is due to variation of solar radiation intensity and other like transportation. The ionosphere differs over the Earth from one place to the other. This is due to variations of the solar zenith angle. The solar zenith angle is the angle

between the local zenith and the line of sight to the Sun. It describes the position of the Sun with respect to the zenith angle. Therefore the ionosphere has considerable variations (Merwe, 2011).

2.12.4 Solar cycle variation

Measurements of the sunspot number, an indicator of solar activity, show that the sun goes through a periodic rise and fall in activity with a period of about 11 years. Since ionization is driven by solar electromagnetic and corpuscular radiation, it is a function of solar activity. At solar maximum the sun emits more radiation and therefore ionization is greater. Thus the critical frequencies of the ionospheric layers are greater during high solar activity periods (Merwe, 2011).

2.13 The Earth's Magnetic Field

2.13.1 Introduction

The Earth's magnetic field is essential for life on Earth, as we know it, to exist. It forms a magnetic shield around the planet, protecting it from high energy particles and radiation from the sun by partially blocking it out, which can cause damage to life, power systems, orbiting satellites, astronauts and spacecraft's. However, there is always some part of the plasma and radiation that is able to penetrate through the magnetic field barrier, and this often leads to magnetic disturbances around the Earth. Before electricity became a basic need of a daily life, the magnetic disturbances did not have a large effect on life on Earth. In modern times, the need to understand the behavior of the Earth's magnetic field, its origin and variations, is becoming ever

more important. With intense research, focused on both the surface of Earth, and the Sun-Earth environment, the goal is to be able to predict the behavior of the magnetic field just as meteorologists predict the weather.

2.13.2 Properties and Origin of the Earth's magnetic field

The Earth has a magnetic field which is mainly produced within its interior and forms a protecting shield around the planet, called the magnetosphere (Edda Lina Gunnarsdottir, 2012). The magnetosphere protects Earth's inhabitants from the highly energetic and dangerous particles from the sun and it prevents the Earth's atmosphere from being blown away by the solar wind and (Brekke, 2008). According to magnetized rocks as old as 4 billion years, found in Greenland and Australia, the magnetic field already existed in the beginning of Earth's history (Meloni and Lanza, 2006).

2.13.3 Source of Magnetic Field Contributions to the total Magnetic Field

The observed magnetic field on Earth is called the geomagnetic field. It is a superposition of magnetic fields generated by different sources (Edda Lina Gunnarsdottir, 2012). The field generated by a magnetic dynamo in the Earth's liquid core is called the main field and is by far the most dominant one. The main field and the crustal field, which is generated by magnetized rocks on the Earth's crust, are categorized as the internal field and are rather stable in time compared to the external field (Edda Lina Gunnarsdottir, 2012). The external field is composed of the field produced by the electric currents called space source field in the ionosphere and magnetosphere. Generally, the geomagnetic field components which make up the total geomagnetic

field are, most dominantly internal and space source magnetic fields (Edda Lina Gunnarsdottir, 2012). As mentioned above, the main field is produced in the interior of the Earth by a self-sustaining dynamo (Edda Lina Gunnarsdottir, 2012). The magnetic field is produced by circulating electric currents in the highly conductive outer core. The complex motion of the currents (or the fluid conducting material), is driven by convection and the rotation of the Earth. The non-homogeneity of the electric currents causes regional magnetic anomalies on the Earth's surface and variations in the main field are connected to variations in the fluid velocity (Meloni and Lanza, 2006). Before the theory of a non-trivial dynamo in Earth's interior, there were suggestions that the Earth's magnetic field was produced by a strong permanent magnet located in its center. However, ferromagnetic material, like iron in the Earth's core, cannot be magnetized above their Curie temperature, the temperature at which a magnet loses its magnetism. The temperature in the Earth's core is much higher than the Curie temperature of iron. In fact, at the depth of a few tens of km the temperature is higher than the Curie temperature of almost all known ferromagnetic materials (Jankowski and suksdorf, 1996). According to this there must be electric currents in Earth's interior producing the field.

2.14 The Geometry of the Earth's Magnetic Field

The geomagnetic field has a direction and magnitude at every point in space and thus is a vector field. The absolute strength of the magnetic field on Earth's surface varies from 23,000 nT to 62,000 nT (Matzka et al, 2010). It is strongest around the poles and weakest around the equator but between the two, the variation in the strength is not linear. The field both varies with space and time,. In the polar regions

the magnetic field consists more or less of a vertical component and at the equator the field lines lie in the horizontal plane. The location at which the field is purely vertical are called south and north magnetic poles and they are not the same as the geographical poles marked by the Earth's rotation axis. As implied in figure 2.10, the Earth's magnetic field is like the field of a magnetic dipole. It is as if there were a giant bar magnet located at the center of the planet, tilted 11.5 degrees from the Earth's rotational axis.

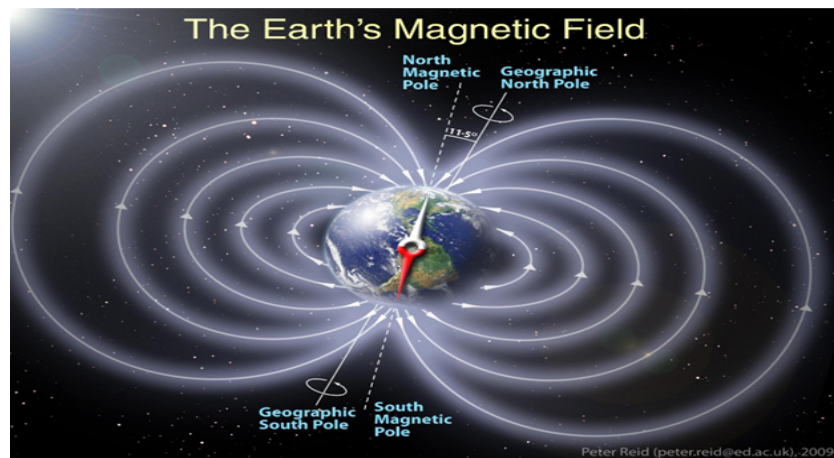


Figure 2.10: Geographic and geomagnetic poles of the Earth (Nave, 2012).

The locations where the magnetic poles and Earth's magnetic field was purely dipolar are called the geomagnetic poles.

2.15 The Magnetosphere

The Earth and its magnetic field is highly affected by its neighboring star, the Sun. The Sun is continuously emitting ionized gas, consisting of electrons, ionized hydrogen

and helium. This constant stream of plasma, moving at speeds of 250-2000 km/s, is called the solar wind (Love, 2008). The solar wind carries with it the solar magnetic field which fills up the interplanetary space and is called the interplanetary magnetic field (IMF). The low density plasma from the Sun and the IMF shape the Earth's magnetic field, which is actually quite different from the dipolar field mentioned earlier. The area in which the Earth's magnetic field dominates and controls the motion of particles is defined as the magnetosphere.

Figure 2.11 shows the different characteristic regions within the magnetosphere and how the solar wind shapes the magnetosphere. On the sun ward side of the Earth, the magnetosphere is compressed due to the solar wind, and has a paraboloidal surface called the magnetopause. The magnetopause is the outer limit of the magnetosphere (Love, 2008).

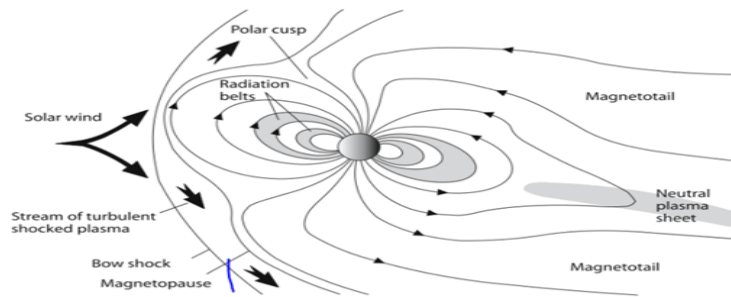


Figure 2.11: The Earth's magnetosphere and it's characteristic regions (Meloni and Lanza, 2006).

2.16 Magnetospheric currents

When the solar wind, moving with an average velocity of around 400 km/s with respect to the Earth, collides with the magnetosphere, a bow shock is formed (Merrill and McElhinny, 2010). This happens at a distance of around 13 Re. On the Earth's dark side, the magnetosphere stretches far out into space, more than 100 Re, forming the magneto tail. Within the tail there is a plasma sheet. In this plasma sheet there are electric currents which affect the geometry of the magneto tail. The magnetosphere shields the Earth from the incident solar wind but there is always some amount of electrons and ions, that are able to penetrate through the "shield" and after that become a part of the magnetosphere. The trajectory of charged particles in the magnetosphere is governed by the Lorentz force which makes the particles spiral around the magnetic field lines, moving back and forth between the poles. When the charged particles approach the polar regions, where the magnetic field lines are more dense and the field is stronger, they slow down as being repelled, and bounce back to the other hemisphere. When they reach the other hemisphere the process is repeated, and so on. These particles, surrounding the Earth and traveling back and forth between the hemispheres, form the Earth's radiation belts. There are two regions in particular, where particles get trapped, and they are called the inner and outer Van Allen radiation belts. Some particles are energetic enough to be able to penetrate down to the Earth's upper atmosphere. Then, they collide with atoms and lose their energy. These collisions lead to the auroras because atoms in the Earth's atmosphere get excited by the collision and emit electromagnetic radiation in the visible range this radiation is the auroras. The shape of the magnetosphere is dependent on the solar activity. When solar activity is high, more intense solar winds makes the solar side of

the magnetosphere compress towards Earth and the tail stretch back. This also means that larger amounts of particles are able to get within the magnetosphere, causing complicated current systems and short term time disturbances in the magnetic field. Another way to describe the magnetosphere is in terms of its constituent electric currents shown in figure 2.12. The magnetospheric current systems has general features which can be separated into three smaller systems; The magnetopause current, the ring current and the magneto tail current system. The magnetospheric current system is quite complicated (Jankowski and sucksdorff, 1996). The magnetopause current is defined by a drift of charged particles which make up an eastward current near the equatorial plane (Love, 2008). The magnetotail currents consist of a westward equatorial current sheet (Love, 2008). The ring current is located between two and seven Earth radii. It is caused by trapped particles in the radiation belts because ions drift westward and electrons eastwards. This longitudinal drift gives rise to a net westward equatorial current sheet (Jankowski and sucksdorff, 1996). There exist also currents flowing along magnetic field lines, field aligned currents, mainly carried by electrons, which connect the magnetospheric currents with ionospheric currents. The current magnitude decreases as the magnetopause moves farther from the Earth where the magnetic field is weaker. Observers close to the Earth's surface (e.g. magnetic observatories, aircraft and low-orbiting satellites), see the combined magnetic field of all of the magnetospheric currents. This magnetospheric field has a strength of up to 50 nT during magnetically quiet times (<http://info.geomag.us/magnetosphere.html>).

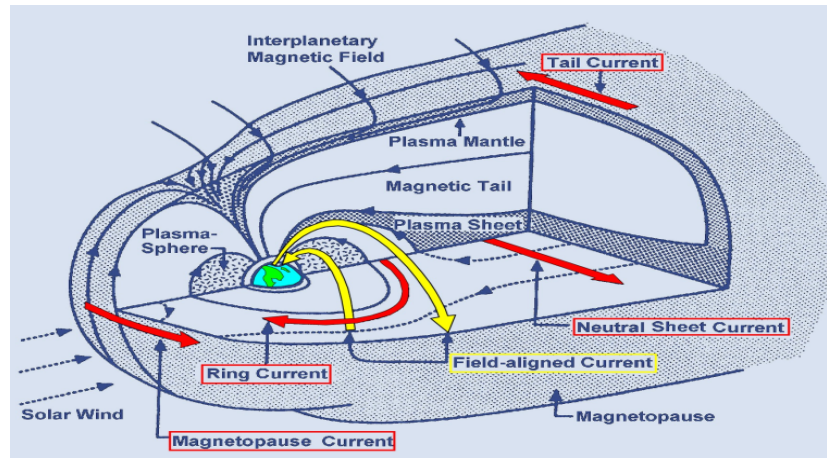


Figure 2.12: Electric currents in the magnetosphere (<http://info.geomag.us/magnetosphere.html>).

The lower boundary of the magnetosphere marks the upper part of the ionosphere. In the F region Large currents can be produced in the ionosphere, especially in the F_2 region where charged particles are subjected to electromagnetic forces (Merrill and McElhinny, 1983). Particles in the ionosphere are also affected by tidal forces and thermal effects which can cause electric currents.

2.17 Variations of the Earth's magnetic field

2.17.1 Time Variation

Geomagnetic field measurements and other geological studies show that the Earth's magnetic field changes significantly with time (Edda Lina Gunnarsdottir, 2012). The time variations can be from the scale of seconds up to millions of years, they can be periodic or completely random, they can include changes in declination or inclination

and the field's total strength can vary from a few nT up to thousands of nT. The time variations are divided into two main groups, Long and short term variations (Edda Lina Gunnarsdottir, 2012). What distinguishes them, apart from the duration, is that long term variations come from the dynamics of the Earth's interior, whereas short term variations have an external origin (space source). The long term variations are on a scale of 5 years or more and are called secular variations. They appear as main field variations. The short term variations can be on the scale of seconds or more but their duration hardly exceeds a year. They often cause intense variations in the field and are mainly produced by currents in the magnetosphere and ionosphere. The rapidity and intensity of these variations makes them very obvious in magnetic observatory data (Meloni and Lanza, 2006). At times, when the intensity and direction of the geomagnetic field vector is constantly changing, the field is said to be magnetically active and periodic variations due to the rotation and orbital motion of the Earth, Sun and Moon are included in the group of short term variations (Edda Lina Gunnarsdottir, 2012).

2.17.2 Long Term Variations

The existence of the secular variation was discovered in 1634, when geomagnetic measurements showed that the declination of the Earth's magnetic field was not only a function of position, but also of time (Jankowsk and sucksdorff, 1996). Today, the intensity and the inclination of the main field are known to vary with time as well. These changes are rather small but still well recognizable when looking at geomagnetic data ranging over several years. The total intensity of the Earth's magnetic field can vary from a few nT per year to tens of nT per year and the declination and

inclination can vary from a few minutes per year to several minutes per year. The secular variation and the main field both originate from the same source within the Earth's interior. Thus, the secular variation gives important information about the dynamics of the conductive fluid in the Earth's core and the origin of the geomagnetic field itself. One of the main applications of research on the secular variation, is to improve and construct new theoretical models that simulate the current system which generates the geomagnetic field. The field reversal is change in the declination by 180° and reversal of the sign of the inclination (Meloni and Lanza, 2006).

2.17.3 Short Term Variations

Short term variations can be divided into regular variations caused by the orbital motion and or rotation of celestial bodies, and irregular variations. Short term variations in the geomagnetic field are related to variations in the external field (space source) (Edda Lina Gunnarsdottir, 2012).

Irregular Variations

What causes irregular variations in the geomagnetic field, is the interaction between the magnetic field of the solar wind, and the magnetosphere. The interaction, involving transfer of plasma and energy, leads to time varying currents in the magnetosphere and ionosphere. Sudden and repeated (but not regular) changes in the magnetosphere are called a geomagnetic storm. These magnetic disturbances can cause variations of 1– 1000 nT and they effect all the elements of the geomagnetic field. A geomagnetic storm occurs when a large amount of energy and plasma has been transferred from the solar wind to the magnetosphere.

The duration of a magnetic storm can be a few hours to several days. Magnetic storms are, in fact, usually a sum of several sub storms, which are minor, localized disturbances in the field mainly evident at high latitudes. Sub storms can occur individually and they are believed to form when energy builds up in the magnetotail causing a magnetic reconnection (Love, 2008). The process of magnetic reconnection is when two oppositely directed magnetic field lines are brought together and magnetic energy is converted into plasma kinetic energy, making it possible for plasma to flow along the field lines (Mullan, 2010). When this takes place in the magnetotail, particles are accelerated towards the poles, along the Earth's magnetic field lines. The collision between these accelerated particles and atoms in the upper atmosphere give rise to the auroras. Because of this, there is a direct connection between auroral display and magnetic disturbances. During minor perturbations in the field, auroras can be observed at high latitudes but they can only be seen at lower latitudes during intense magnetic storms. The sun is continuously blowing the solar wind towards Earth, but that, in itself, is not enough to cause large variations in the field, although it can lead to minor disturbances. The rapid and intense disturbances occur when an unusually large amount of plasma and burst of radiation is ejected from the Sun. The magnetosphere then responds by deforming drastically, leading to the measured magnetic perturbations on Earth. If the magnetic field of the incoming solar wind is aligned with the Earth's magnetic field, the magnetosphere was thought to act like a strong shield against it, and the solar particles would then slide around the magnetosphere. But with the opposite orientation it could more easily deposit magnetic energy and radiation into Earth's environment. In addition to the stream of particle radiation from sun, the solar X-ray and UV-radiation can amplify the ionospheric

current systems so much that large affects are measured in the geomagnetic field (Merrill and MCElhinny, 1983).

Regular Variations

Regular variations of the geomagnetic field are due to the Earth's rotation and its orbital movement around the sun. The diurnal variations, also called solar daily variations, are the most prominent of the regular variations. It is believed that electric currents flowing in the E-layer of the day side ionosphere are the main cause of the diurnal variations. During the daylight hours on Earth, the solar radiation ionizes the upper atmosphere, increasing the density of ions that make up the currents in the ionosphere. The current system in the ionosphere, which causes the diurnal variations, is driven by winds from the day-night temperature difference and electrically conducting tidal winds (Love, 2008). On the night side, the currents in the ionosphere are negligible (Love, 2008). The regular diurnal variations depend on the time of year, solar activity and the geomagnetic latitude and longitude. days when there are no stronger magnetic disturbances are called solar quiet days, Sq. And days, when the magnetic field is active, are called solar disturbed days or SD (Meloni and Lanza, 2006). The field gets disturbed more often close to the equinoxes than at other times of the year (Meloni and Lanza, 2006). It is believed that the reason for this is the solar wind effect, that has great role for the variation of the field when the center of the sun is in the same plane as the Earth's equator. That happens when Earth is at the equinoxes. At those times, it would be more likely that the solar plasma hits the Earth.

Chapter 3

Methodology

3.1 Measurements

Measurements of the Earth's magnetic field make possible to study the interior structure of the Earth and the complex current dynamo in its core which produces the geomagnetic field itself. The measurements give information on the currents in the ionosphere and magnetosphere. They reveal relations between magnetic disturbances and solar activity, as well as relations of magnetic activity to auroral display. Measurements of the magnetic field also make it possible to monitor magnetic storms, with the conceivable result of predicting their behavior in the future. These magnetic measurements are carried out by scientists all over the world studying the different phenomena. The most important factors regarding geomagnetic measurements are accuracy, temporal continuity and vast geographical coverage. The compass was the first instrument used to measure the geomagnetic field direction. According to ancient literature, the Chinese were the first to take advantage of the practical use of magnetism by using compasses for nautical navigation in the 11th century.

The declination of Earth's magnetic field, its deviation from geographical north, was most likely known in China long before Europeans discovered it (Merrill and McElhinny, 1983). The observation that the compass needle tilted with respect to the horizontal plane marked the discovery of inclination in about 1510. More than 200 years later, in 1785, Charles-Augustin de Coulomb found a way to measure the intensity of the horizontal component of the Earth's magnetic field. But it was not until 1832, when Carl Fredrich Gauss discovered a way to measure the total intensity of the magnetic field, that techniques for measuring all the geomagnetic field components were available. At that time, regular measurements of the field components had been made and it was already known that all components varied with time.

3.2 Geomagnetic Observatories

At present time, measurements of the Earth's magnetic field vector are carried out at approximately 170 geomagnetic observatories around the world (Love, 2008). A geomagnetic observatory is a place where continuous measurements of the geomagnetic field are made for long period of time with the best possible accuracy. Modern observatories produce their data in digital form and depending on the quality of the observatory, one-minute or one-second-average digital data are reported with the accuracy of 1nT. Observatories typically consist of A fluxgate variometer that measures the intensity of the field in X, Y and Z direction, a fluxgate theodolite, which yields the declination and inclination of the field, and a proton precession magnetometer, which measure the total intensity (Danish, 2006). Absolute measurements have to be performed regularly (preferably once a week) at observatories. They are performed

to correct for instrumental drift and other possible errors. The location of an observatory needs to meet certain criteria, they cannot, for example, be close to any magnetic disturbances. The magnetic measurements are all ground based. The goal of every observatory is to have the highest possible accuracy and to avoid gaps in the recordings. To produce high quality data, the geomagnetic measurements need to be homogeneous over long time and have an accuracy of 1 nT. The recordings of modern observatories should ideally be universally accessible, for instance on the internet (preferably showing the real-time vector field) and every year observatories should release their final data (St-Louis, 2011). The site of an observatory needs to meet a number of requirements for the observatory to satisfy certain criteria. It should be able to produce data within the desired accuracy and to be able to operate for a long time—hundreds of years even. Thus, the site has to be chosen carefully. The environment around the observatory, within a radius of several km distance, needs to be checked, because there cannot be any crustal magnetic anomalies close by, possible induced currents, nor other kinds of changes in magnetic properties. Factors like the high conductivity of seawater and man made disturbances also need to be taken into account. Variometers are designed to be extremely sensitive so the material in the buildings housing them has to be nonmagnetic. The absolute measurements are performed, the sensitivity of the measurements are even higher. The present needed for magnetic observatories at high-latitude areas is due to their special role in a number of studies connected with magnetospheric phenomena, and also in the equatorial region, where the behavior of the equatorial electro jet needs detailed study.

3.3 INTERMAGNET

INTERMAGNET represents International Real-time Magnetic Observatory Network. The standards for geomagnetic observatories are decided by INTERMAGNET, is a global network of magnetic observatories which advocates magnetic observatory to produce high-quality data, and makes geomagnetic recordings easily accessible on the internet. Recently, INTERMAGNET has encouraged observatories to upgrade their data products to perform 1 Hz data (1 second data) and to constantly correct their data acquisition with a temporary baseline to meet the modern needs of the scientific society. Satellite observations cannot yet replace the traditional ground-based observatories, because the life-times of satellite missions are relatively short, at most 10 years. The INTERMAGNET program exists to establish a global network of cooperating digital magnetic observatories, adopting modern standard specifications for measuring and recording equipment, in order to facilitate data exchanges and the production of geomagnetic products in close to real time. A large number of geomagnetic observatories throughout the world are members of INTERMAGNET. The data availability is 1 minute data since 1991, 1 second data from some stations since 2009.

3.4 Magnetometers

The instruments used for measuring the field vector are typically a variometer and proton magnetometer. The triaxial fluxgate variometer is an instrument that continuously records three vector components and the proton magnetometer also operates

continuously but it only measures the total intensity of the magnetic field vector. The total intensity values, obtained from the variometer and proton magnetometer, are constantly being compared because a change in the difference between them could mean a problem in one of the instruments. Finally, the fluxgate theodolite is used to measure the declination and inclination of the geomagnetic field (Danish, 2006). And simultaneous measurements, performed by the proton magnetometer, give the total intensity of the field. By combining the results from the two instruments, an absolute value of the geomagnetic field vector is obtained. This procedure is therefore called an absolute measurement.

Generally Continuous measurements of the Earth's magnetic field are performed by magnetic observatories worldwide, which have the combined goal of recording magnetic data with the highest possible accuracy and to avoid gaps in the recordings. For this study magnetic field data obtained from equatorial region INTERMAGNET observatories have been used for the year 2011 and 2012 (for annual mean). Large number of geomagnetic observatories throughout the world are members of INTERMAGNET. The magnetic field data obtained from five equatorial region stations at different longitudes and magnetic dip latitude have been used for the study. The stations used are shown in the Figure 3.1. The magnetic and geographic latitudes of the stations are presented in Table 3.1.

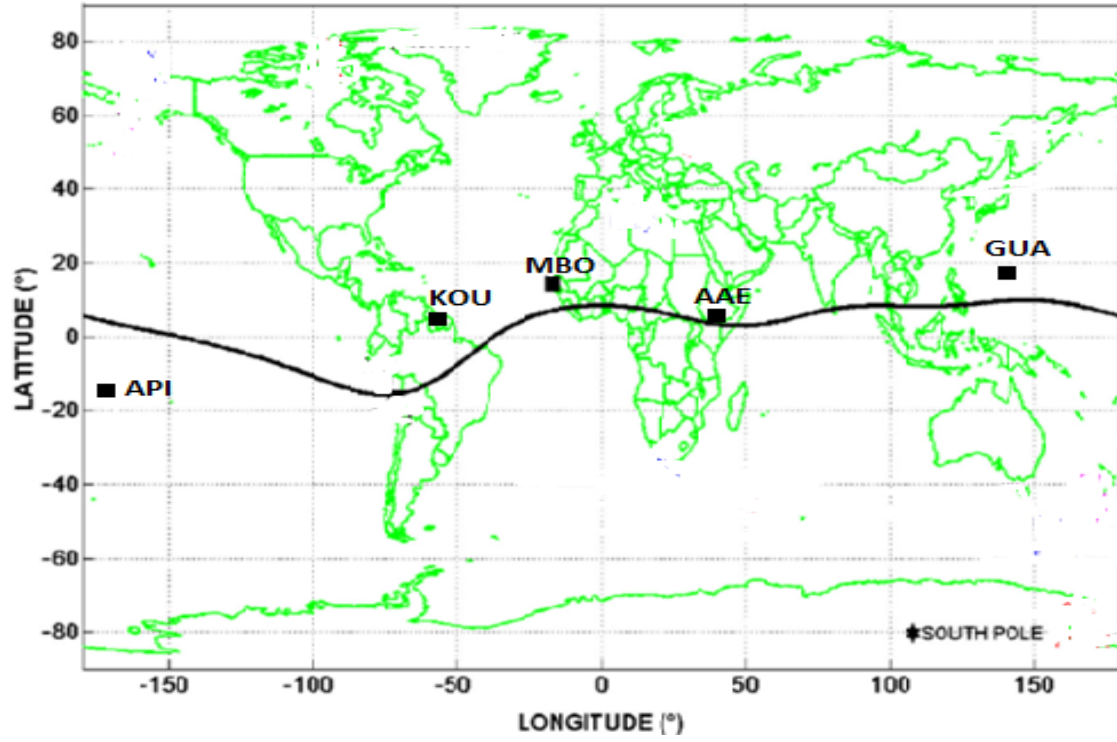


Figure 3.1: Map of INTERMAGNET Geomagnetic stations being used.

Stations	Geog.longitude	Geog.latitude	Dip latitude	Geom.latitude
AAE	$38.76^{\circ}E$	$9^{\circ}N$	1.86	5.3
API	$171.75^{\circ}W$	$13.8^{\circ}S$	29.9	-15.4
GUA	$144.79^{\circ}E$	$13.44^{\circ}N$	12.1	5.3
KOU	$52.64^{\circ}W$	$5.2^{\circ}N$	16.9	11.9
MBO	$16.96^{\circ}W$	$14.42^{\circ}N$	7.65	20.1

Table 3.1: INTERMAGNET equatorial region magnetic observatory stations used.

As we have seen from the Table 3.1 the geographical location of stations are at equator regions. The data's are received or loaded from ([www. intermagnet.org/data-donnee/](http://www.intermagnet.org/data-donnee/)). Then MATLAB codes were developed to plot the graphs and analyze the data. The study investigates the spatial and temporal variability of space source magnetic field along equator regions. The space source magnetic field is obtained by subtracting mean of night time magnetic field from the total observed magnetic field. Because, the source of the magnetic field at night time is considered to be originated only from the Earth core (interior) and at the day time the sources of the field are both the core and the space (Edda Lina Gunnarsdottir, 2012). The values of the horizontal component of the space source magnetic field at the selected stations were plotted by extracting the space source magnetic field from the total magnetic field and the variability of the field strength has been discussed..

Chapter 4

Result and discussions

4.1 Introduction

In this chapter we are going to analyze the spatio-temporal variation of space source day time horizontal component of the Earth's magnetic field estimated from the INTERMAGNET data for the year 2011 and (2012 for annual mean) in equator regions. The temporal variation is investigated in terms of daily, monthly, seasonal and annual mean variation of the space source day time Earth's magnetic field and spatial variation is the latitudinal and longitudinal variations in equator regions. The field strength was described both in the dip equator and outside of it. The result is analyzed first and then discussion will be followed.

4.2 Daily mean Spatial variation of space source Earth's magnetic field

Figure 4.1 shows the diurnal variation of the space source magnetic field obtained at different longitude and magnetic dip latitude during March, May, August and December in the year 2011. As we have seen in this Figure the space source magnetic field varies from station to station. In all of the days shown in this figure the space source day time magnetic field strength obtained at AAE station is the largest of all of the stations. And minimum noon time space source magnetic field is found at API and KOU stations as shown in table 4.1. This shows that the magnetic dip latitudinal variation of space source day time horizontal component of the Earth's magnetic field dominates longitudinal variation for each day in equator regions.

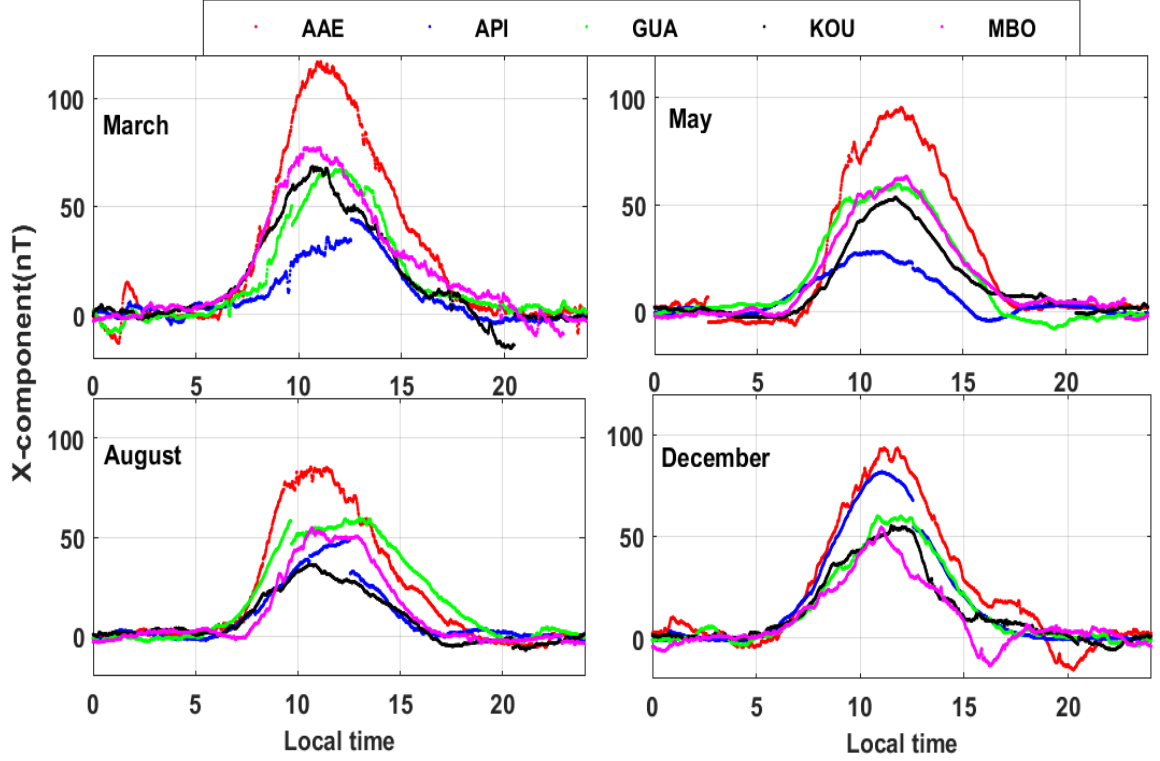


Figure 4.1: Sample of daily mean spatial variability of space source magnetic field in the same day (6^{th}) in each station.

It is possible to understand from the Figure 4.1 and Table 4.1 that AAE station magnetic field strength is peak and the day time field strength in API and KOU stations is minimum. That AAE station is in the dip equator and API station is far from the dip equator. As we go far from the magnetic dip equator the field strength decreases and longitudinal variation is dominated by the distance variation from the magnetic dip equator. This could be one of the manifestation of intensified equatorial electron jet in the dip equator of AAE station and its effect is observed upto API of dip latitude -29.9° but decreasing in strength. In AAE station mean diurnal variation of the space source day time horizontal component of the Earth's magnetic

stations		march	May	August	December
AAE(38.78^0E)(dip lat. 1.86^0)	Field(B)	117nT	95.24nT	85.29nT	93.51nT
API(171.75^0W)(dip lat. -29.9^0)	B	44.2nT	29.97nT	48.38nT	81.77nT
GUA(145.79^0E)(dip lat. 12.17^0)	B	67.03nT	59.37nT	59.16nT	59.88nT
KOU(52.64^0W)(dip lat. 16.9^0)	B	67.96nT	53.3nT	35.93nT	55.35nT
MBO(16.96^0W)(dip lat. 7.65^0)	B	77.16nT	63.18nT	54.71nT	54.41nT

Table 4.1: Daily mean spatial variation maximum values of the space source magnetic field in the stations in a day of six.

field ranges from 85.29 nT (a day in August)-117 nT (day in March), in API it ranges from 29.97 nT (a day in May) - 81.77 nT (a day in December), in KOU it is from 35.93 nT (a day in August) - 67.96 nT (a day in March), in GUA it is also from 59.37 nT(a day in May) -67.03 nT(a day in March) and in MBO the range is from 54.41 nT (a day in December) - 77.16 nT (a day in March). These shows that AAE, MBO, GUA and KOU have maximum space source magnetic field in a day in March which is equinox days, and API has maximum day time magnetic field strength in a day in December. The time ranges at which the magnetic field strength obtained maximum is from 10.63 LT to 12.58 LT for each station, maximum day time field strength obtained at the noontime.

4.3 Monthly mean Spatial variation of space source Earth's magnetic field

Figure 4.2 shows monthly variation of space source magnetic field at different longitude and dip latitude such as AAE, API , GUA, KOU and MBO. As seen from this figure the peak magnitude of space source magnetic field obtained at AAE is the largest during all months. The figure shows space source day time magnetic field strength was maximum around 12.00 LT, at the noon time. As we can observe from figure 4.2 the magnetic field strength varies depending on their magnetic dip latitude location of stations other than their longitudinal locations which is dominated.

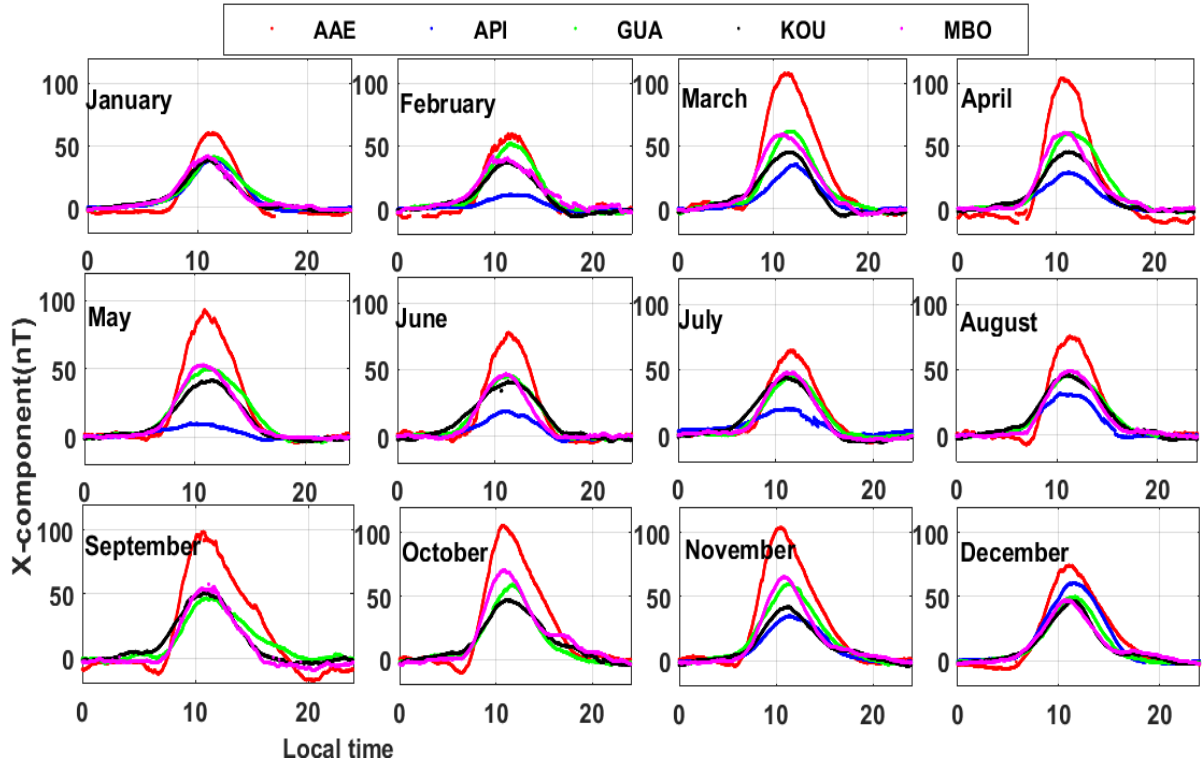


Figure 4.2: Monthly mean Spatial variability of space source magnetic field along equatorial regions.

As we can see from Table 4.2 the day time magnetic field strength in AAE station peaks over the other stations and the field strength is minimum in KOU and API. The magnetic field strength depends on the distance from the magnetic equator which dominates the longitudinal variation of the field. For example the AAE ($39^{\circ}E$) found in between the other observatory stations in longitudinal location but in the magnetic dip equator has peak magnetic field strength in each month. The field strength increases near to the dip equator and decreases away from it. The peak magnetic field strength in AAE and minimum field strength in API could be due to different equatorial dynamics of the ionosphere.

month	AAE	API	GUA	KOU	MBO
Jan	60.1nT	40.16nT	40.56nT	40.56nT	41.74nT
Feb.	59.77nT	11.06nT	53.39nT	36.97nT	41.68nT
March	107.8nT	35.66nT	61.68nT	45.06nT	59.19nT
April	104.1nT	28.89nT	60.52nT	45.16nT	60.82nT
may	92.8nT	9.63nT	49.65nT	41.35nT	53.32nT
June	77.88nT	18.93nT	40.88nT	40.86nT	46.81nT
Jully	64.63nT	19.99nT	47.63nT	43.86nT	47.84nT
Aug.	75.45nT	30.99nT	45.58nT	45.78nT	49.18nT
Sept.	98.48nT	no data	46.86nT	51.14nT	57.81nT
Oct.	105.3nT	nodata	58.31nT	47.01nT	70.45nT
Nov.	103.8nT	34.85nT	60.05nT	41.95nT	65.4nT
Dec.	74.39nT	60.66nT	50.01nT	46.78nT	47.14nT

Table 4.2: maximum value of space source magnetic field in each month and station at noon time.

That is the generation of currents (equatorial electro jet (EEJ)) by electromotive forces due to tidal winds in the dip equator enhances the Earth's magnetic field in day time. According to Agbo et al, (2017) equatorial electron jet is higher in the dip equator sectors in AAE and strongest in equinox season. So, the magnetic field strength induced by such intensified east ward current (EEJ) in the dip equator of AAE station causes the space source magnetic field to peak of all stations. And minimum field strength obtained in API which is far out of the EEJ region (far from the magnetic dip equator). For the entire longitudinal sectors the EEJ has its maximum in the noontime (Agbo et al, 2017). So that, the strength of the space source magnetic field peaks in the noontime.

The magnetic field strength over AAE station is maximum followed by MBO, GUA, KOU and API respectively. This is in order of the distance from the dip equator not in longitudinal order. Away from the dip equator the day time field strength decreases. The day time magnetic field strength of the stations in API, MBO, KOU and GUA which all are out of the EEJ region is not the same. This shows us the presence of effect of EEJ out of 6° and -6° from the magnetic dip equator but decreasing in strength away from the magnetic dip equator. In February and December GUA and API magnetic field strength has irregularity respectively. And such magnetic storm in a station out of the dip equator is important to compare the storm field strength with the field strength by intense EEJ in the dip equator. Temporally the field strength in AAE station is maximum in march (107.8nT) and relatively minimum in January (60.1nT), In API it is relatively maximum in December (60.66nT) and minimum in May (9.63nT), in Guam it is maximum in March (61.68nT) and minimum in January(40.56nT), in KOU the field is maximum in September (51.14nT) and minimum in February (36.97nT) and in MBO it is large in October (70.45nT) and minimum in February (41.68nT).

Figure 4.3 shows monthly mean spatial variation of the space source Earth' magnetic field for the year 2011. In this figure AAE space source Earth's magnetic field is the largest of all in each month and peak in March, in API it is high in December, in GUA which is high in March, KOU high in September and MBO maximum in October. The maximum field recorded in each station is in the noon time. This Figure shows that space source magnetic field varies significantly with magnetic dip latitude which dominating the longitudinal variation. That magnetic dip latitudinal variation is more significant than longitudinal variation of the field.

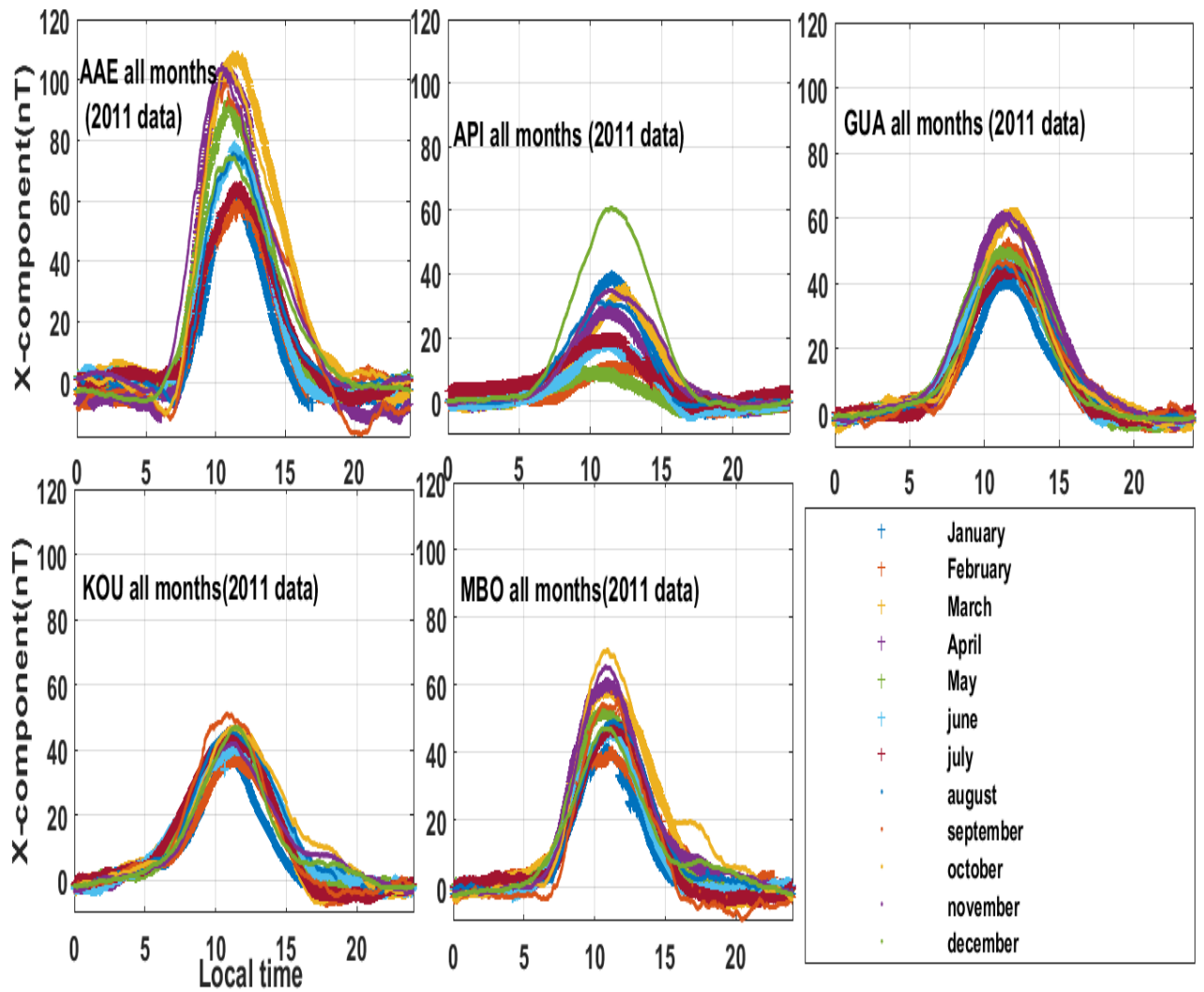


Figure 4.3: Monthly variation of space source magnetic field at different stations such as AAE, API, GUA, KOU, and MBO for the year 2011.

4.4 Seasonal mean Spatial variation

Figure 4.4 shows the variation of space source magnetic field in each season of AAE, API, GUA, KOU and MBO. The magnetic field strength in AAE station is peak of all stations in each season. And minimum space source magnetic field is obtained in API and KOU with especial storm in API in December solictice. The field strength follows magnetic dip latitude location other than longitudinal location of the stations. That the magnetic dip latitude location is more important than longitudinal location for the variation of space source Earth's magnetic field over the stations. The field strength increases near to the dip equator and decreases away from it due to strength in equatorial electro jet and it' effect exist even far from the dip equator.

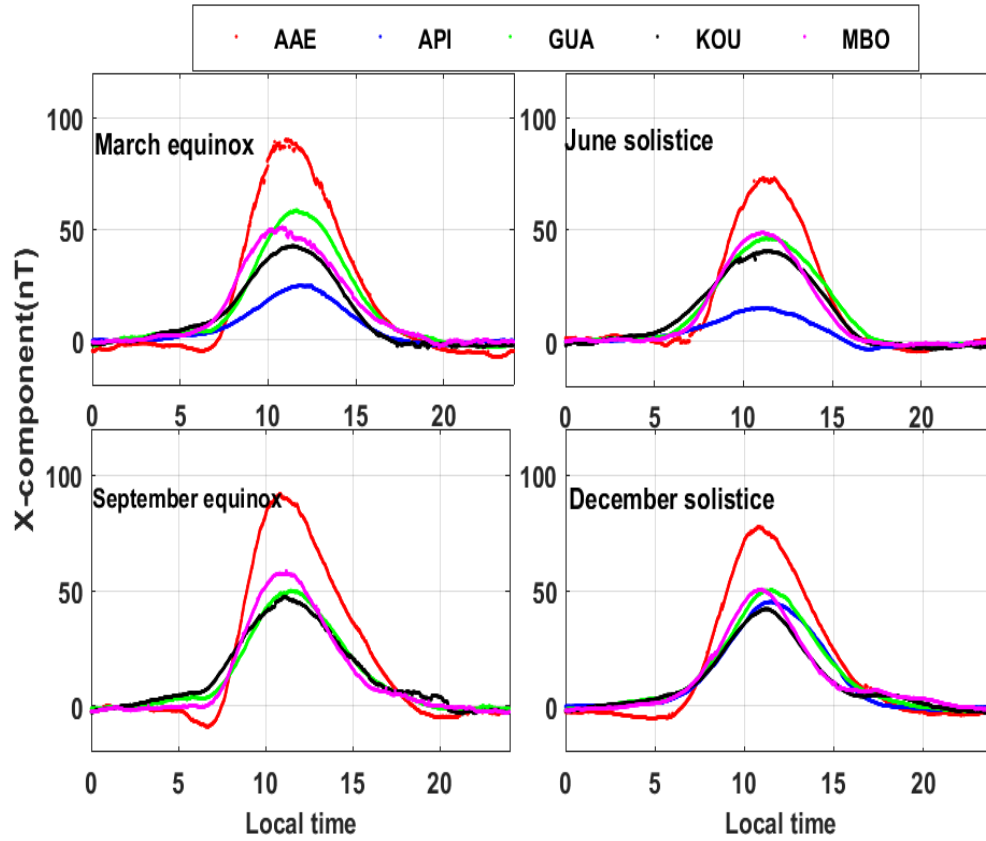


Figure 4.4: Seasonal spatial variation of the space source magnetic field along equator regions.

As the station is far from the dip equator the space source magnetic field strength decreases. The increment of space source magnetic field near to the dip equator is directly related to high strength of equatorial electron jet in the dip equator.

Observatories	March equinox	June solstice	September equinox	December solstice
AAE($38.78^{\circ}E$)	90.05nT	73.01nT	91.92nT	77.38nT
API($171.75^{\circ}W$)	24.52nT	14.91nT	-	45.04nT
GUA($144.79^{\circ}E$)	58.35nT	46.03nT	49.93nT	50.22nT
KOU($52.64^{\circ}W$)	43.31nT	40.24nT	47.1nT	42nT
MBO($16.96^{\circ}W$)	50.69nT	48.72nT	58.47nT	50.55nT

Table 4.3: Maximum values of the space source Earth's magnetic field in equator regions in each season.

And for the overall station the peak space source magnetic field strength is recorded in the noontime. The maximum magnetic field strength of the stations in each season is shown in table 4.3. Seasonal mean space source magnetic field strength in AAE in the dip equator is maximum in September equinox (91.92nT), the field strength in API is relatively maximum in December solstice (45.04nT), in GUA it is maximum in March equinox (58.35nT), in KOU it relatively high in September equinox (47.1nT) and finally for MBO the maximum mean value is recorded in September equinox (58.47nT). In AAE the space source magnetic field strength still peaks of all stations in each season. And mostly the magnetic field strength is maximum in the equinox seasons for all observatory stations.

4.5 Annual mean spatial variation

Figure 4.5 shows annual mean spatial variability of space source magnetic field obtained at different longitude and dip latitude for the year 2011 and 2012 in equator regions. In AAE station magnetic field strength peaks of all the stations. And minimum space source magnetic field strength is recorded in API station. For the year 2011 space source magnetic field strength in AAE station is maximum (81.75nT) followed by MBO (53.42nT), GUA (51.25nT), KOU (40.4nT) and API (29.11nT) respectively. And for the year 2012 again AAE station magnetic field strength (82.52nT) peaks followed by MBO (56.25nT), GUA (54.85nT), KOU (44.6nT) and API (38.1nT) respectively. The field strength is directly related to magnetic dip latitude location of stations that dominates longitudinal variation. Far from the magnetic dip equator the space source magnetic field strength decreases. And higher field strength in AAE found in the dip equator (dip latitude 1.8°). The field strength is minimum in API ($171.75^\circ W$) which is relatively far from the dip equator (dip latitude -29.9°). The day time magnetic field strength varies in equator regions according to the distance from the magnetic dip equator than their longitudinal variation. This shows the presence of the effect of equatorial electro jet out of 6° (out of the EEJ zone) but decreasing in strength away from it upto the limit of this study API (dip latitude of -29.9°).

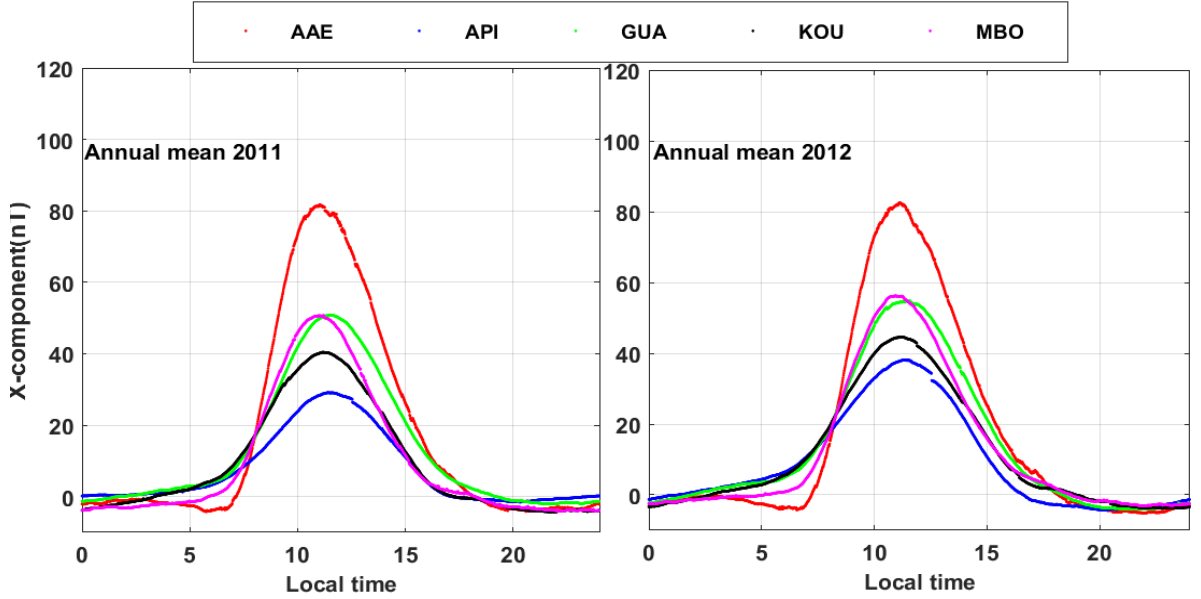


Figure 4.5: Annual mean spatial variability of space source Earth's magnetic field strength in the year 2011 and 2012.

In general the spatial variations show that magnetic dip latitudinal variation of the space source magnetic field is more significant than longitudinal variation of the field. Such kind of variability could be due to different equatorial dynamics of the ionosphere. The equatorial ionosphere is unique in many ways. Global scale dynamo action, generation of currents by electromotive forces due to tidal winds, results in the generation of planetary scale West East electric fields at low latitudes around the dip equator. Above the magnetic equator, the geomagnetic field lines are horizontal to the Earth's surface, which result in different geophysical phenomena peculiar to the equatorial region. These are: Equatorial Electro jet (EEJ), equatorial ionization anomaly (EIA) and generation of plasma irregularities (Agbo et al, 2017). Due to the especial geometry of global scale dynamo electric field E in the west east direction and the geomagnetic field B in the south north direction over the magnetic equator,

electrons drift vertically with respect to ions and due to limitation of vertical extent of dynamo E-region, a vertical polarization electric field sets up. This vertical polarization electric field results in the enhanced conductivity in the eastward direction. This large current is known as the Equatorial Electro jet (Agbo et al, 2017).

According to Agbo et al, (2017) equatorial electron jet is higher in the dip equator sectors in AAE and for the entire longitudinal sectors the EEJ has its maximum in the noontime. So, this study result shows the space source magnetic field strength correlates with the strength of EEJ. That is, the field strength is maximum in noon time.

With no disregarding other factors contribute to the space source magnetic field equatorial electro jet (EEJ) in the dip equator contributes great to enhance space source magnetic field. Therefore it is possible to deduce that the main cause for the increment of space source magnetic field near to the dip equator and decrease in far away from the dip equator is intensified eastward current (equatorial electron jet) in the dip equator and decreasing its strength away from it. That could be the reason why the space source Earth's magnetic field strength in AAE station is greatest over the other stations.

The location of the geomagnetic equator (or dip equator) is usually described as the locus of zero dip along the surface of the Earth, in which EEJ is maximum (Kelley, 2009). That AAE found in the dip equator has greatest equatorial electron jet and peak day time magnetic field.

The Earth's atmosphere is most exposed to Sun's ionizing radiation, lead to various geomagnetic and ionospheric phenomena, many of which are unique to the region (Kelley, 2009). Then the field strength is dominantly dependent on the magnetic dip

angle for a region like the character of EEJ described above.

The ionosphere carries electric currents, because, winds and electric fields drive ions and electrons in different directions. So, the conductivity in the ionosphere could be one factor for the increment of the space source magnetic field in the dip equator. Therefore these variation of space source magnetic field in different stations could be due intense equatorial region electron jet (EEJ) that plays a great and magnetospheric currents in the dip equator. And less strengthen EEJ with different magnetospheric currents causes the space source magnetic field to be relatively peak at day time out of the magnetic dip equator. But the combined magnetic field enhanced by all of the magnetospheric currents has a strength of up to 50 nT during magnetically quiet times (<http://info.geomag.us/magnetosphere.html>). Then the day time magnetic field by magnetospheric currents creating far from the surface of the Earth is not large compering to the field by EEJ. So, we can understand that the strength of equatorial electron jet (EEJ) is maximum in the dip equator and exists out of 6° and -6° from the dip equator but decreasing further in strength.

Chapter 5

Conclusion and Recommendations

5.1 Conclusion

This study investigated that the space source horizontal component of the Earth's magnetic field exhibits spatio-temporal variation in equator regions. The magnetic dip latitudinal (distance from magnetic dip equator) variability of space source Earth's magnetic field is more significant than longitudinal variability of space source Earth's magnetic field along equator regions. The space source magnetic field strength in Adiss Ababa (AAE) found in the dip equator peaks of all the stations. In Adiss Ababa(AAE) (dip latitude 1.8°) the field strength is maximum followed by MBO (dip latitude 7.65°), GUA (Dip latitude 12.1°), KOU (Dip latitude 16.89°) and API (Dip latitude -29.9°) respectively. In Addis Ababa (AAE) it displayed the highest amplitude (maximum field strength), while in API minimum space source magnetic field strength is obtained. The space source magnetic field strength is maximum near to the magnetic dip equator and decreases away from it. This could be the manifestation of high equatorial electron jet in the dip equator and decreasing further

in strength out of the dip equator upto API of 29.9° from the dip equator. This shows that the contribution (strength) of equatorial electron jet (EEJ) out of 6° and -6° from the dip equator is nonzero but decreasing further in magnitude. Therefore the space source horizontal component of the Earth's magnetic field varies from station to station dominantly based on their distance from magnetic dip equator. The cause for the space source magnetic field is the intensified equatorial electron jet and other sources (like, magnetospheric currents) in the magnetic dip equator. And the less strengthen EEJ with magnetospheric currents contribute for the enhancement of space source Earth's magnetic field out of magnetic dip equator. The study also investigated that the space source magnetic field is peak in the noon time mostly in March, September and in equinox seasons.

5.2 Recommendation

We investigated the spatio-temporal variation of space source magnetic field using data from equatorial regions of AAE, MBO, API and KOU for the year 2011 and 2012. And the study clearly showed the result discussed above. But if we like to view the dominated longitudinal variation of space source magnetic field, it is possible to use magnetic data obtained from the dip equator stations for example data from Peru station which is in the dip equator in addition to AAE. That AAE and Peru stations are found at different longitude and both are in the magnetic dip equator. For this study the Peru data is not available in the INTERMAGNET for the year.

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Declaration

I,here by declare that the thesis is my original work and has not been presented for a degree in any other university,and that all sources of materials have been duly acknowledged.

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This thesis has been submitted for the examination with my approval as University advisor.

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