

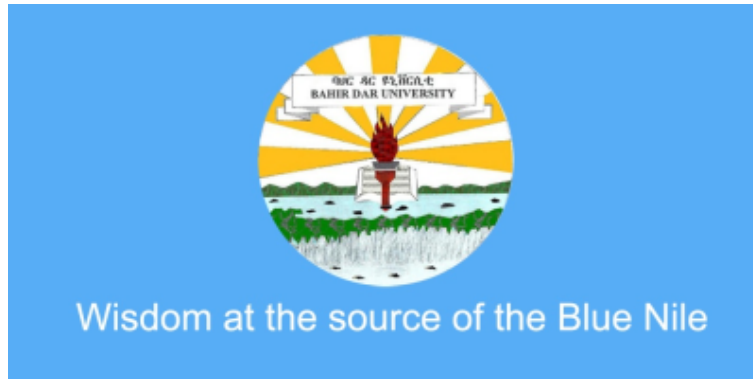
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STUDYING THE VARIABILITY OF THE IONOSPHERE USING SUPERSID MONITOR AND SWARM SATELLITE DATA

Meseret, Lingerew

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STUDYING THE VARIABILITY OF THE IONOSPHERE USING
SUPERSID MONITOR AND SWARM SATELLITE DATA

BY

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Bahir Dar, Ethiopia

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June, 2019

CERTIFICATION

The undersigned hereby certify that they have read and recommend to the school of postgraduate studies for the acceptance of this project work entitled: **"STUDYING THE VARIABILITY OF THE IONOSPHERE USING SUPERSID MONITOR AND SWARM SATELLITE DATA"** by **Meseret Lingerew** in Partial Fulfillment of the Requirements for the Degree of **MASTER OF SCIENCE IN PHYSICS** at Bahir Dar University.

APPROVED BY:

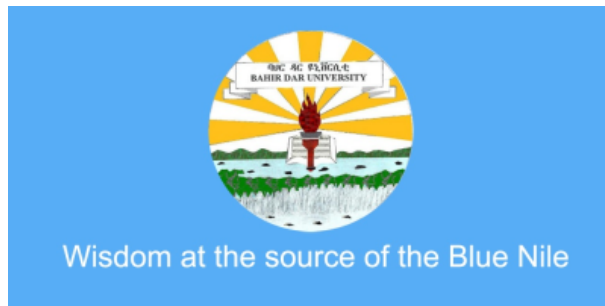
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STUDYING THE VARIABILITY OF THE IONOSPHERE USING
SUPERSID MONITOR AND SWARM SATELLITE DATA



A Thesis Presented to
the School of Postgraduate Studies Bahir Dar University
in Partial Fulfillment of the Requirements for
the Degree of
MASTER OF SCIENCE IN PHYSICS

BY

Meseret Lingerew

June, 2019

AUTHORIZATION TO COPY

Meseret Lingerew hereby authorizes the Bahir Dar University to copy and/or release the whole, part of this research work to other researchers and organizations wishing to use the material for reference and/or research purposes.

This work is dedicated to Mr. Andargie Gerawork!

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Abstract

Variability of the Earth's ionosphere is a threat for applications that depend on trans-ionospheric propagating radio waves. Characterisation of its variability is the first step to make correction. In this thesis, a sudden ionospheric disturbance (SuperSID) monitor has been deployed at Bahir Dar, Ethiopia and the variability of the ionosphere due to solar events is investigated using the SuperSID monitor and the recently launched Swarm satellite data. The VLF signal strength data collected by SuperSID and in situ ion density observed by Swarm have been analysed. Plots of VLF signal strength data showed the daytime and night-time variations of the radio signal strength that are results of the variability of the ionosphere in these time intervals. The signal strength variations are captured as sunset and sunrise signatures with sharp rise and sharp drop of the signal strength respectively.

Our analysis of the Swarm satellite data also depicted that from 7.35-9.61 UT of 22 June, 2015, the dayside ionosphere showed suppressed EIA while the nightside is strengthened indicating the first CME of the day had resulted a disturbance dynamo. However, from 13.55-22.14 UT the PPEF was the dominant driver of the variability. Hemispheric asymmetry of geomagnetic effect was also observed during this event. Moreover, the EIA in the Pacific sector was the strongest of all during the June 22, 2015 geomagnetic storm while the African sector had the highly suppressed EIA in the daytime. Comparison of the daytime and nighttime recovery showed the nighttime ionosphere has recovered sooner than the daytime.

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

The ionosphere of any planet is the portion of the atmosphere where free electrons and ions of thermal energy exist under the control of the gravity and magnetic field of the planet. Therefore, the ionosphere of the Earth is defined as the region of the upper atmosphere where ions and electrons of thermal energy are present in quantities sufficient to affect the propagation of radio waves (IEEE, 1998). This region makes up less than 1% of the mass of the atmosphere of the Earth and it extends from about 50-1000 km. It is formed when solar radiation (extreme ultraviolet, EUV and x-ray) liberates electrons from neutral atoms and molecules in the Earth's atmosphere.

The solar radiation is absorbed differently by the neutral atmosphere at different altitudes and hence ionosphere is divided into different layers: D Layer (from 50 to 90 km), E Layer (from 90 to 150 km) and F Layer (over 150 km). During the day the F layer splits into F1 and F2 layers. Sudden enhancement of the solar radiation in the X-ray and EUV band during a solar flare can produce great changes of the ionospheric electron density on the dayside of the Earth and thus affects the radio wave propagation (Donghe & Zuo, 2000). The other mechanism the Sun can

affect the Earth is it ejects large, violent plasma and magnetic fields in a state where electrons have been separated from the nuclei of their atoms (Scherrer *et al.*, 2015; CENTRA Technology, Inc., 2004). This bundle of matter, which is the origin of geomagnetic storms and primarily affects the Earth's magnetosphere, is called a Coronal Mass Ejection (CME). The coronal mass ejections (CMES) result geomagnetic storms by increasing the speed and/or density of the solar wind, which can be associated or not with solar erupta (de Abreu *et al.*, 2014).

Johnson *et al.* (2016) stated, solar events such as Coronal Mass Ejections (CMEs), solar flares and associated recombination events are the driving factors in space weather and the solar wind intensity. Even though it is located at such a great distance from our nearest star, the space and time-variable conditions in the space environment affect space-borne or ground based technological systems and, in the worst case, endanger human health or life on the ground or in space (Hanslmeier, 2004). For example, high frequency (HF) and very low frequency (VLF) radio signals can be reflected back to the Earth at F and around the bottom of E region, respectively while the D-region absorbs the propagating signal. On the other hand, the total electron content along the ray-path between Global Positioning Satellite (GPS) and receiver delays the GPS signal and consequently results in positioning error (Kintner & Ledvina, 2005). Moreover, the rapid fluctuation of the electron density highly affects the trans-ionospheric signal (Basu *et al.*, 1999). The effects of space weather can range to endangering astronauts on a mission to the Moon or Mars, damage of satellites and disruption of power grids on Earth. Similarly, Clausen *et al.* (2017) proposed solar flares can lead to so-called radio blackout storms which disrupt communication systems operating at high-frequencies while large geomagnetic storms caused by CMEs result

in strong ionospheric currents which induce current in the ground and lead to failure of power grid operations. The 29th October, 2003 storm (the Halloween Storm) is reported as one of such storms destroying power grids in Sweden and South Africa, and extensive satellite problems were reported. The March 17-18, 2015 storm is the other disruptive and largest storm in the 24th solar cycle ([Astafyeva *et al.*, 2016](#)).

To understand altitudinal, latitudinal, longitudinal, diurnal, seasonal and solar and geomagnetic activity variations of the ionosphere, space science community has been deploying different space weather monitoring instruments around the world ([Amory-Mazaudier *et al.*, 2009](#)). Swarm is one of the Earth Explorer Missions run by the European Space Agency (ESA) and was successfully launched on Nov. 22, 2013 comprising three identical satellites, Alpha (A), Bravo (B) and Charlie (C) ([Astafyeva *et al.*, 2016](#)). The principal goal of the Swarm Mission is to study the way the Earth's geomagnetic field varies over space and time and to investigate the ionospheric environment. In this space weather monitoring campaign, the African region has been given attention due to the unique equatorial ionospheric phenomena exhibited in the region ([Hei *et al.*, 2005](#)).

Scientists of the field have been in endeavour to investigate the threats and the enormous influences of space weather and ionospheric weather, though the concern isn't to them alone. Source identification of geomagnetic storms, modeling the interactions of geomagnetic field with power grids, understanding past events and predicting the effects of future geomagnetic storms (having space weather nowcast and forecast) to mitigate the impacts on Earth and mankind's activities are the main concerns of the space science community.

1.2 Statement of the Problem

Monitoring the ionosphere with the help of radio signals is an active branch of research today. Therefore, ground based stations and satellite applications are built and launched around the globe to investigate the variability of the ionosphere. Using different parameters measured by these instruments, many researchers have investigated the response of the ionosphere to solar flares and geomagnetic storms in different sectors. For example, [Maoa *et al.* \(2017\)](#) investigated the response of the equatorial and low-latitude ionosphere over the West Pacific Ocean Sector to an X1.2 solar flare of May 15, 2013 using TEC data. Moreover, [Buresova & Lastovicka \(2001\)](#) and [Danilov \(2013\)](#) studied the response of ionospheric F-region to geomagnetic disturbances using electron density data; and foF2 (the highest frequency the ionosphere can reflect vertically) and TEC data respectively.

On the other hand, [Seba & Nigussie \(2016\)](#) investigated the effect of geomagnetic storm on equatorial ionospheric irregularity over East African sector using magnetosphere and TEC data. Besides, [Tesema *et al.* \(2015\)](#) used GPS-TEC data from East Africa longitudinal sector to study the response of the ionosphere to intense geomagnetic storms in 2012. Similarly, [Kassa & Damtie \(2017\)](#) investigated ionospheric irregularities over Bahir Dar, Ethiopia during selected geomagnetic storms using TEC data. However, there are no adequate investigations of the response of the ionospheric F-region electron density to geomagnetic storms using Swarm satellite data. [Astafyeva *et al.* \(2016\)](#) studied the extreme topside ionospheric response to the June 22-23, 2015 geomagnetic storm using the Swarm constellation electron density data. But they concentrated

only on the initial and final phases of the event. Therefore, this thesis work attempts to investigate the response of the top ionospheric region to an intense geomagnetic storm using electron density data from Swarm satellite which is a high resolution in situ measurement.

The second task of this work is deploying Super Sudden Ionospheric Disturbance (SuperSID) monitor and using its data to study the response of the ionosphere to solar flares. In 2017, one SuperSID receiver has been donated to the Washera Geospace and Radar Science Laboratory (WaGRL) Research Center, Bahir Dar, Ethiopia by Stanford Solar Center, USA. After building its VLF (Very Low Frequency) antenna, the SuperSID monitor will be deployed. Then a VLF radio signal from different stations around the world will be picked and we will collect SuperSID data. Using the collected data, the effect of the ionosphere on VLF radio signals will be analysed. This device will complement other space physics facilities in WaGRL.

1.3 Objectives

General Objectives

The main aim of the thesis work is to investigate the ionospheric variability due to solar events.

Specific Objectives

The specific objectives of this work are:

- To build a VLF antenna and deploy a SuperSID monitor at Bahir Dar, Ethiopia.

- To collect SuperSID data and investigate the effect of the ionosphere on VLF signals.
- To investigate the response of the topside of the ionosphere to the 22-23 June, 2015 geomagnetic storm using Swarm satellite electron density data.

1.4 Significance of the Study

This work will report the variability of the ionosphere by solar events. It will have a significant contribution to the Washera Geospace and Radar Science Laboratory of Bahir Dar University, especially space research activities. The Swarm satellite data analysis results will contribute to ionospheric studies worldwide. Generally, the thesis work will bring the following significances.

- It will enable us to get hands-on practice on how to design an antenna using simple antenna wires and trap radio transmissions.
- It can be used to provoke students' and teachers' interest about science in general and about radio propagation in particular.
- It can be used as a springboard for future students and scientists to try other more sophisticated designs, which may be used to assist our day-to-day life activities.
- It will enrich our understanding of the effect of the ionosphere on radio signal propagation.

CHAPTER 2

The Sun and Earth's Ionosphere

2.1 The Sun

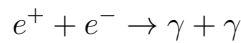
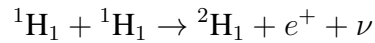
The Sun as a star is defined as a huge ball of hot gas under the influence of gravitational force that is balanced by the pressure exerted by the gas, so that an equilibrium size the Sun prevails. It is our nearest star in the Milky Way Galaxy with average mass of 1.99×10^{30} kg, radius 6.96×10^8 m, gravitational acceleration on the surface 272 m/s^2 and luminosity 3.9×10^{26} watts which is classified by Astrophysicists as a star of average size, temperature and brightness. Its average temperature 5800 Kelvin at the surface and 15.5 million Kelvin in the core. The continual radiation output of the Sun has allowed life on Earth, and virtually all the energy supply for Earth's surface and atmosphere originates from this star.

The Sun is composed of mainly from Hydrogen and Helium. Its composition by mass is 74% H, 25% He and 1% other elements. By number of atoms, the composition is 91.2% H, 8.7% He and 0.1 % other elements. Our planet Earth is showered by solar radiation due to the process that the Hydrogen nuclei are turned into Helium nuclei that takes place in the core of the Sun. The process is termed as **nuclear fusion**.

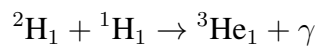
2.1.1 Thermonuclear Fusion Reaction in the Sun

The nuclear fusion reaction, which occurs only at very high temperatures, is responsible for the production of the first 26 elements heavier than Hydrogen in stars. But because of relatively small mass of the Sun, only the first two stages of fusion will occur in the core of the Sun, the Hydrogen-Helium stage and the Helium-Carbon stage. As the Sun is relatively a low central temperature star the dominant energy comes from the first stage when it turns Hydrogen nuclei into Helium nuclei in its core. This process is also a three-stage process called proton-proton (pp) cycle or pp chain. The three pp chain stages are:

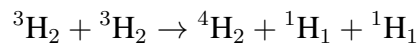
1. Two protons collide giving a deuteron, positron (e^+) and neutrino (ν) . Charge of one of the proton is carried away by the positron which is the antiparticle of the electron. The positrons of this stage encounter an electron and both are annihilated and converted into two gamma ray photons.



2. A third proton colides with the deuteron to give a Helium-3 isotope emitting a gamma ray.



3. The above two steps are carried out twice. Then two Helium-3 nuclei collide to give one Helium nucleus and two protons.



In the three-step pp chain, a net four Hydrogen nuclei are turned into a Helium nucleus. One Helium nucleus has 99.3% of the weight of four Hydrogen nuclei. It is this excess of 0.7% of Hydrogen mass compared with Helium mass converted into energy and released in fusion reactions as mass is equivalent to energy from Einstein's relation $E = mc^2$. Each second, 600 billion kg of Hydrogen is fused leaving the Sun to lose 4 billion kg of its mass.

2.1.2 Interior Structure of the Sun

Different mechanisms operate to transport the energy produced in the Sun outwards. These energy propagation mechanisms define the interior structure of the Sun. Based on that, it is classified into three regions. They are the core, the radiative zone and the convective zone.

2.1.2.1 Core

The core is the region of energy generation via nuclear fusion. It is the high-density and high-temperature gas at the center of the Sun extending about 25% of the solar radius and containing about 1.6% of the volume of the Sun. One half of the solar mass is contained in this region, despite its radius is only one fourth of the solar radius. The core of the Sun has temperature of about 15 million Kelvin and density of 160 g cm^{-3} .

Since the core is the continual energy generation region, i.e., Hydrogen is continuously converted into Helium, the composition of the core is slowly changing. The process began with 71% Hydrogen and 27% Helium. After 4.6 billion years, a substantial fraction of the Hydrogen in the core has been converted to Helium. By 10 billion years, the core will be totally Helium.

2.1.2.2 Radiative Zone

The radiative zone is an internal region of the Sun extending from the core boundary out to 70% of the Sun's radius. This region is less dense than the core. The radiation generated in the core reaches the outside in a way the photons are continually absorbed and re-radiated by the material in the radiative zone. A typical photon moves only 0.09 cm between consecutive collisions. Therefore, it takes on average about 170 thousand years to reach the surface of the Sun, moving in a zigzag journey at an average speed of 0.01 cm s^{-1} .

The temperature in the interior of the Sun decreases towards the surface. From the core to about 70% of the way out to the surface, it drops to about two million degrees. As a photon moves out from the centre, it is continually absorbed and re-emitted by particles. These particles will have lower and lower energy, so the photon is re-emitted each time with lower energy, and its wavelength becomes longer. The full spectrum of solar radiation is obtained after this process.

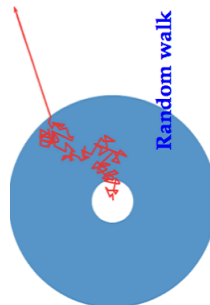


Figure 2.1: The zigzag path of a photon at the interior of the Sun, (Kassa, 2017).

2.1.2.3 Convective Zone

This region is located in the uppermost 30% of the solar interior which occupies only 2% of the solar mass. In the convective zone, energy is transported by bulk motion of gas. The neutral gas blocks the outward flow of heat by absorbing it and becoming extremely hot. Due to the heat absorption the gas expands and becomes less dense than its surroundings. The bundles of hot gas float to the surface of the convection layer, where they radiate away their excess energy. This makes them cooler and denser and sink back down while the hot gas flows upward resulting displacement of particles in the convective zone.

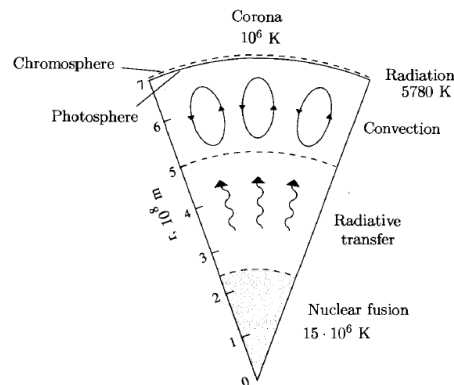


Figure 2.2: Cross Section through the Sun, (Prölss, 2004).

2.1.3 Solar Atmosphere

The solar atmosphere is the layer that lies above the surface of the Sun. Since the Sun is gaseous, there is no rigid boundary marking the start of the atmosphere and end of the interior (Jursa, 1985). However, the solar surface, which is a definite optical surface below it we can't see, can be used as the boundary the solar interior ends and the solar atmosphere starts. Therefore,

moving outward from the solar surface, the solar atmosphere is divided into four layers having characteristic temperatures and densities. The layers are known as *photosphere*, *chromosphere*, *transition zone* and *corona*. These layers are discussed below.

2.1.3.1 Photosphere

The photosphere is the lowest layer in the solar atmosphere where most of the Sun's energy escapes into space. This layer is the part of the Sun that we see with our eyes. It is about 500-600 km thick above the top of the convection zone. In this layer, temperature and density decrease. In the inner part of the photosphere, the temperature is about 7500 K and it decreases to about 4200 K at the top of the photosphere having an average temperature of 5800 K. Convection in the photosphere produces granules which are about 1300 km in size. Sunspots are the other features observed in this layer of the solar atmosphere.

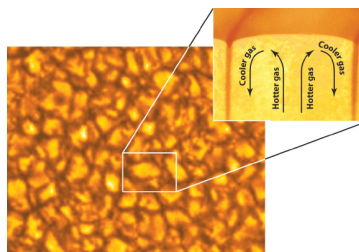


Figure 2.3: Granules in the Photosphere, (Adopted from <https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&cad=rja&uact=8&ved=2ahUKEwjJkJu0vonjAhU4A2MBH\ai1BJ0QFjABegQIABAC&url=http%3A%2F%2Fphysics.gmu.edu%2F~hgeller%2FTeacherWork\shop%2Fch18a.pdf&usg=AOvVaw22c1dMkmT5FmmELptXdI8E>).

2.1.3.2 Chromosphere

Chromosphere is a less dense but higher temperature solar atmospheric layer which is several thousand kilometers thick, transparent glowing gas above the photosphere. Its temperature reaches a value of 9000 K (Brekke, 2013). This layer is characterized by spikes of rising gas called *spicules* which are bright features due to emission from hot ionized gas. The chromosphere comes into view during a total solar eclipse.

2.1.3.3 Transition Region

At the top of the chromosphere is the transition zone where temperature begins a sudden steep rise from 25000 K to 2×10^6 K over a very small spatial range. The spectral lines in this region are in the EUV making it very hard to observe the region. Therefore, it is studied from satellite and rocket observations.

2.1.3.4 Corona

The corona is the faintly visible outermost solar atmospheric layer above the transition region. It is observed using satellite borne *coronographs* which block out the intensive radiation of the photosphere and chromosphere. It is a violent, ever-changing place extending several solar radii from the surface and made of very high temperature gases at extremely low density. Its composition is like the rest part of the Sun. It is made up mostly of Hydrogen with small amount of Helium and traces of heavier elements.

The solar corona is subdivide into three different zones based on dynamical activity there. Their

sizes are different during different phases of the solar cycle. They are active regions, quiet Sun regions and coronal holes with varying sizes in different phases of the solar cycle (Dinku, 2014). Active regions are small portions of the total surface area where most of the solar activities occur and strong mostly closed magnetic field is concentrated so that most of the dynamic processes like plasma heating, flares and coronal mass ejections happen in it (Dinku, 2014). All the closed magnetic field regions that are outside the active regions are the quiet Sun regions. while coronal holes are regions dominated by open magnetic field. Through these open magnetic fields mass is ejected into interplanetary space to form the solar wind. The ejection results in lower plasma density and dark appearance of the coronal holes.

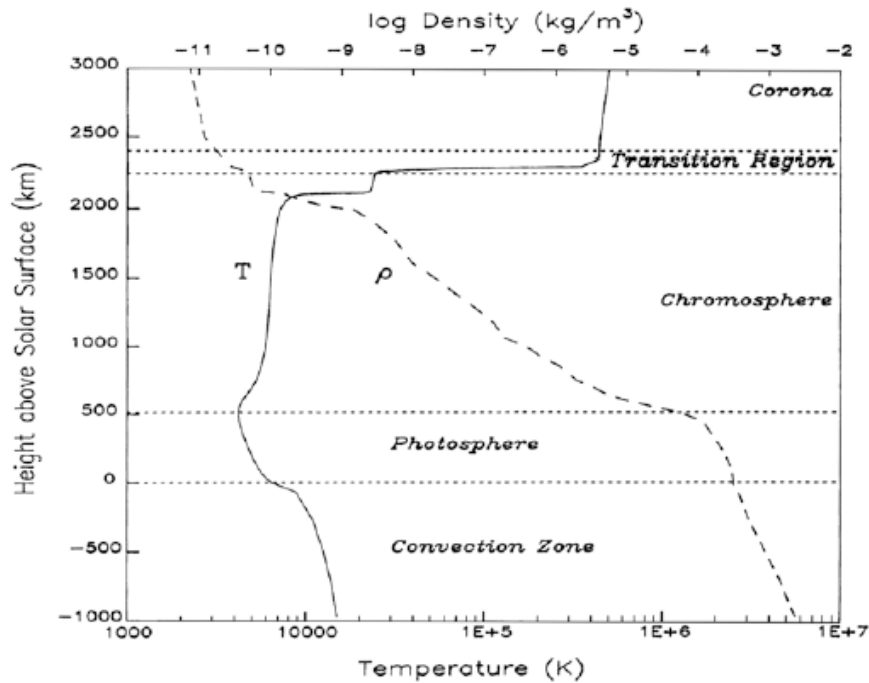


Figure 2.4: Temperature and density profiles in the solar atmosphere, (Brekke, 2013).

2.1.4 Solar Rotation

Since the Sun is not a solid body, its rotation period depends on latitude. Full rotation takes around 28 days near 45° latitude and about 32.3 days near the solar poles. Angular velocity of solar rotation relative to the Earth is given by:

$$\omega_s = 13.4 - 2.7\sin^2\theta_s \quad (2.1)$$

where ω_s is solar angular velocity in $\frac{\text{degrees}}{\text{day}}$ and θ_s is latitude degree from the equator. The rotation period of the Sun relative to the Earth in days is calculated:

$$T_s = 26.9 + 5.4\sin^2\theta_s \quad (2.2)$$

T_s is called a synodic rotation period.

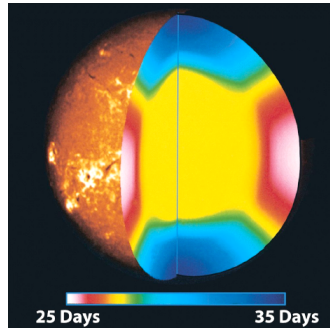


Figure 2.5: Rotation of the Solar Interior, (Adopted from <https://www.google.com/url?sa=t&rct=\j&q=&esrc=s&source=web&cd=2&cad=rja&uact=8&ved=2ahUKEwjJkJu0vonjAhU4A2MBH\ailBJ0QFjABegQIABAC&url=http%3A%2F%2Fphysics.gmu.edu%2F~hgeller%2FTeacherWork\shop%2Fch18a.pdf&usg=AOvVaw22c1dMkmT5FmmELptXdI8E>).

2.1.5 Sunspots

Sunspots are dramatic dark areas in the photosphere. Their darkness is because they are cooler than their bright surroundings having temperature about 2000 K. Their dark centre is called the *umbra* which is surrounded by the lighter *penumbra* that consists of radial filaments. Matter flows outward along these filaments and down above the umbra. The sunspots are formed when an intense magnetic flux tube emerges from the convection zone to the photosphere. The size of these spots range to many times larger than the Earth with diameters up to 20000 km.

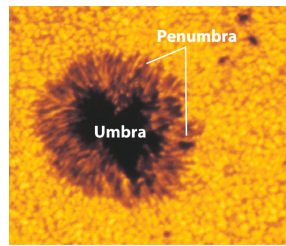


Figure 2.6: Sunspot on the surface of the Sun, (Adopted from <https://www.google.com/url?sa=t&rct=\j&q=&esrc=s&source=web&cd=2&cad=rja&uact=8&ved=2ahUKEwjJkJu0vonjAhU4A2MBH\ailBJ0QFjABegQIABAC&url=http%3A%2F%2Fphysics.gmu.edu%2F~hgeller%2FTeacherWork\shop%2Fch18a.pdf&usg=AOvVaw22c1dMkmT5FmmELptXdI8E>).

The number of sunspots on the solar disk is a most common index of solar activity. The frequency of spots is determined using the relative sunspot number, some times called Zurich or Wolf number that is given as:

$$R = k(10g+s) \quad (2.3)$$

where g is the number of sunspot groups and s is the number of individual spots visible on the solar disk. The constant k is a correction factor which depends on the observer and the conditions of observation. The sunspot number waxes and wanes in an approximately 11-year cycle. But individual solar cycles can vary from 8 to 14 years. For example, the 23rd solar cycle lasted 13 years (Hathaway, 2010).

Sunspots do not appear at random on the Sun's surface, but are concentrated in two belts between latitudes 10 and 30 degrees (Johnston, 2016). At the start of each solar cycle, the spots are found at high latitudes and they move closer to the equator fizzling out near the equator. Therefore, sunspots from a new solar cycle appear at high latitude while sunspots from an old solar cycle are near the equator.

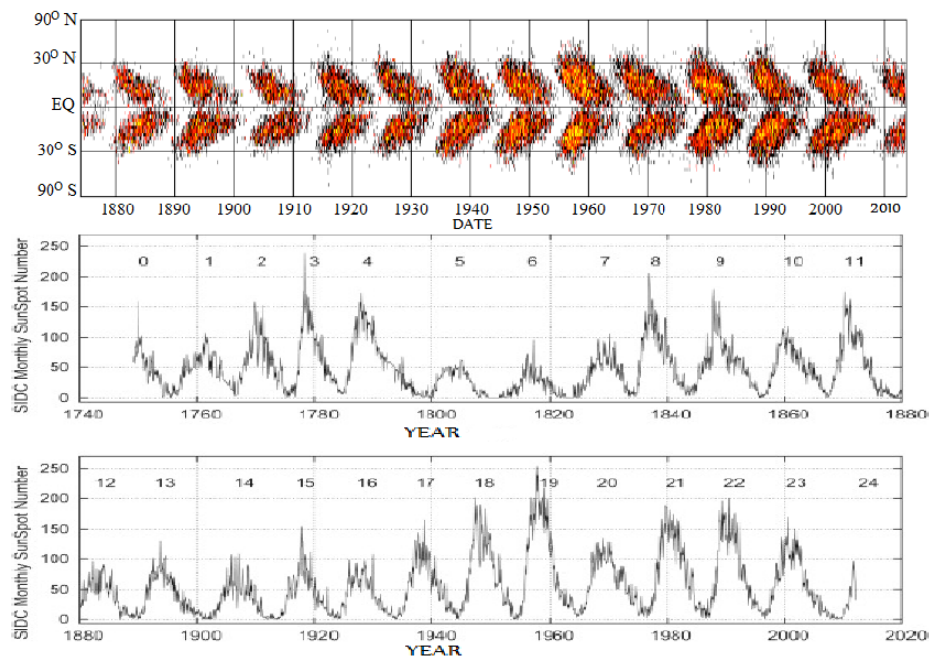


Figure 2.7: The 11-year solar cycle,(Johnston, 2016)

During a given sunspot cycle, leading sunspots have the same polarity in the northern hemisphere, and the opposite polarity in the southern hemisphere. But the magnetic polarity of leading spots changes whenever the cycle changes from one cycle to the next taking a period of about 22 years.

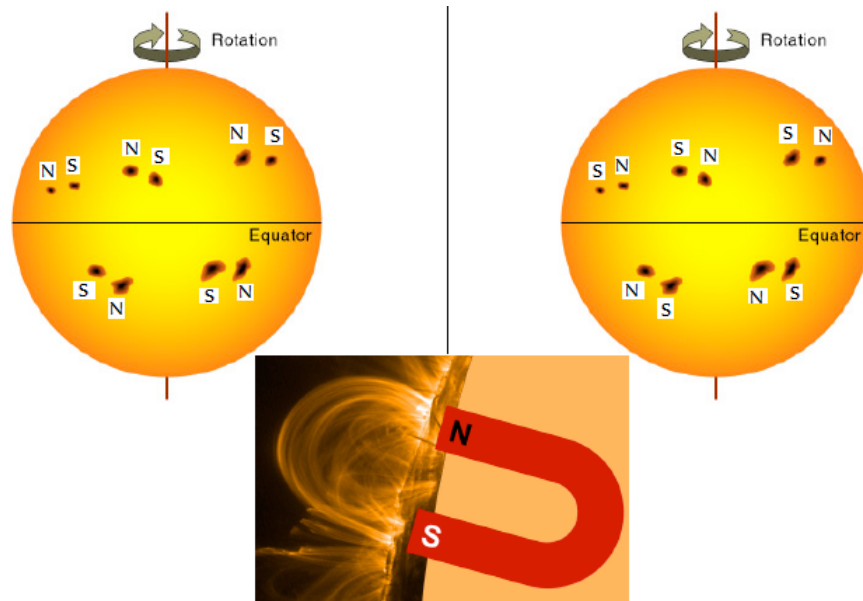


Figure 2.8: Sunspots' polarity change in a 22-year solar cycle, adapted from (Johnston, 2016)

2.1.6 Prominences

Prominences are great areas of luminous material extending outwards from the solar atmosphere and were first observed during eclipses (Hanslmeier, 2004). They are observed as large clouds of gas high above the chromosphere when a filament is seen off the edge of the Sun. These features appear as dark filaments over the photosphere and as bright structures at the limb. Some of them erupt off the edge of the Sun in minutes or hours as enormous gas blobs.

In the prominence's central coolest parts, the temperatures are between 6000 and 8500 K while at the boundary of prominences the temperature rapidly increases to coronal values ,i.e.,more than 1 million K. The plasma density in the central cool parts is about two orders of magnitude larger than that in the corona ([Hanslmeier, 2004](#)).

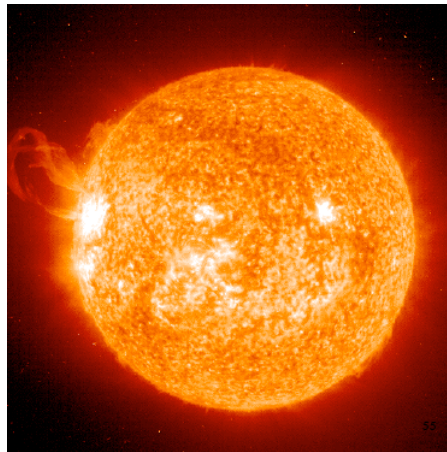


Figure 2.9: Diagram of Prominence, ([Johnston, 2016](#)).

2.1.7 Solar Wind

Solar wind is the continuous mass loss from the Sun. It is a flow of ionised plasma and a remnant of the solar magnetic field that pervades interplanetary space. Its source is solar corona and resulted from the huge difference in gas pressure between the solar corona and interstellar space. The solar plasma is driven outwards because the restraining inward influence of solar gravity is overcome by the outward pressure gradient. The gravitational potential is no longer capable to bound the plasma to the Sun at coronal temperatures so that the plasma can expand out into interplanetary space at supersonic speeds. The Solar wind is responsible for auroras when particles

from it are trapped in the Earth's magnetic field. There are two kinds of solar wind:

1. **Slow Streams:** They originate above and near the closed magnetic field loops and streamers in the corona at about 400 km/s.
2. **Fast Streams:** These kind of solar winds originate in the cooler regions of the corona with open magnetic field lines at speeds approaching 800 km/s.

Since the Sun is in continuous rotation the plasma streams co-rotate and produce a spiral pattern in the solar wind like that of a rotating lawn sprinkler. The quite weak interplanetary magnetic field (IMF), which is only about 1/10000 of the magnetic field at the surface of the Earth, carried out into interplanetary space by the solar wind also travels out in this spiral pattern. Fig.2.10 shows this pattern.

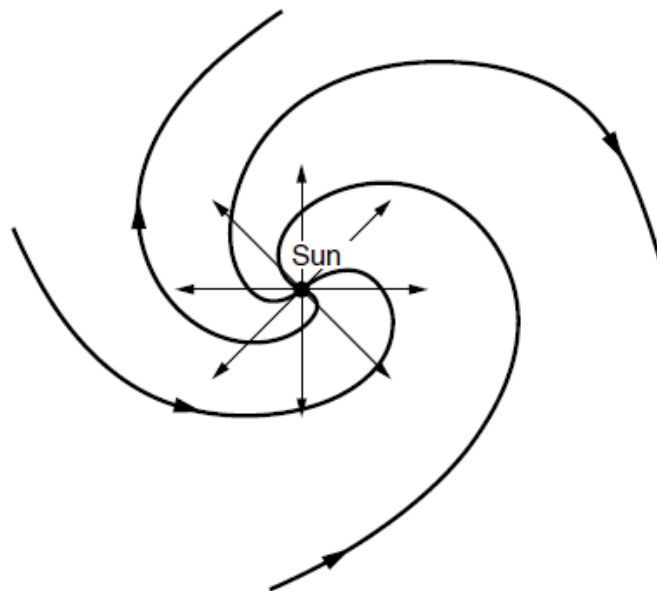
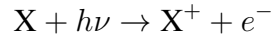
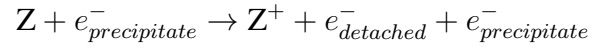


Figure 2.10: The spiral magnetic field as it is stretched out by the solar wind, (Kelley, 2009).

2.2 The Earth's Ionosphere

The ionosphere of the Earth is a weakly ionised gas of the Earth's upper atmosphere consisting of neutral molecules, free electrons and ions. In this region no more than about a fraction of the order of 10^{-3} of the neutral atmospheric atoms and molecules are ionised. Therefore, the mass of neutral molecules and atoms surpasses overwhelmingly that of ions and electrons resulting in neutral molecules and atoms to have a major effect on the motion of the ionised species whereas the effect of the ionised species on the neutral components is weak or slow. Despite it constitutes a very small fraction of atmospheric material, the ionosphere is very important as it influences the propagation of radio waves.

When solar radiation strikes the dominant electrically neutral species of the upper atmosphere of the Earth, electrons are dislodged from atoms and molecules to produce the ionospheric plasma. This process occurs on the day side of the Earth when only the shorter wavelengths of solar radiation (the extreme ultraviolet and X-ray parts of the spectrum) that are energetic enough to produce this ionization strikes the neutral constituents. This ionization mechanism is called **photo-ionization** making the upper atmosphere electrically conductor that supports electric currents. There is another mechanism that ionizes the upper atmosphere of the Earth. It is known as **impact-ionization** in which energetic particles that penetrate the atmosphere collide with the neutral constituents resulting ionization. The two sources of plasma can be represented by the following chemical reactions.

Photo-ionization:**Impact-ionization:**

where X and Z represent neutral atoms or molecules of the atmosphere of the Earth, $h\nu$ is the radiation energy and $e_{precipitate}^-$ represents the ionizing energetic particle. The X^+ and Z^+ terms represent the ionized atoms or molecules of the ionosphere while e^- represents the free electron. Schematically these mechanisms are depicted below in Figure 2.11.

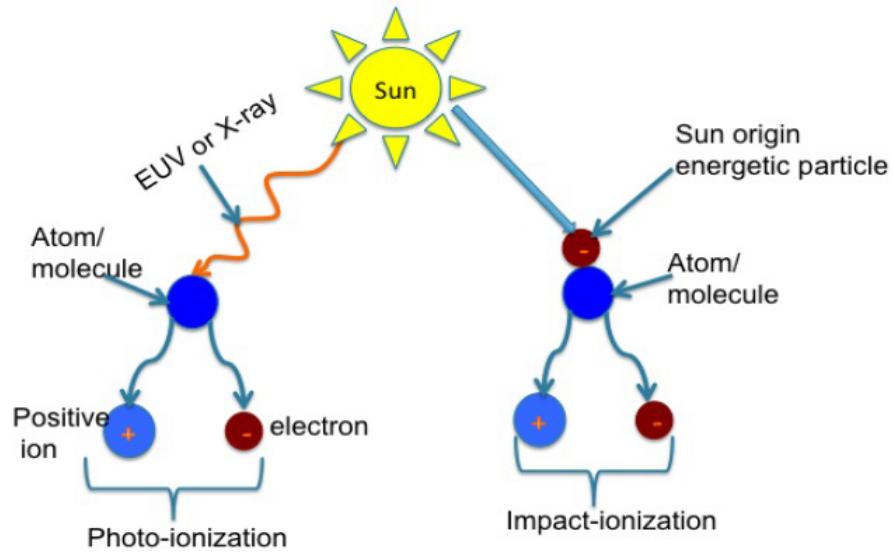


Figure 2.11: Ionization mechanisms, (Kassa (2017) and a reference therein).

The ion production process depends on the neutral density of the atmosphere and radiation intensity from the Sun. The neutral density decreases with altitude while the solar radiation intensity

increases when we go up. As a result, the ion production will have a peak height where neutral density and radiation intensity are optimal. Figure 2.12 shows the peak height of ion production.

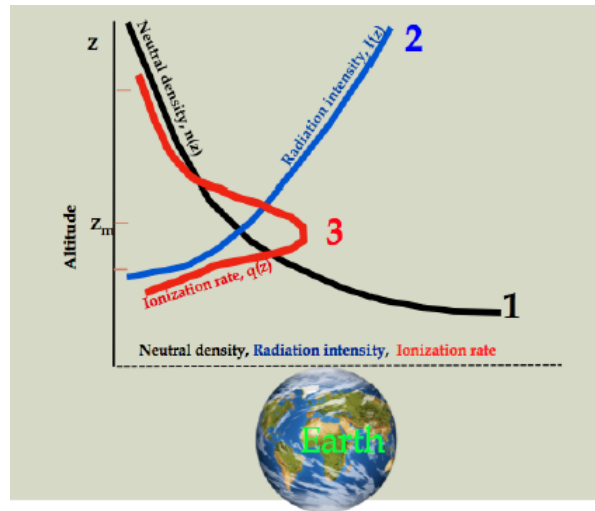


Figure 2.12: Height profile of ion production, (Kassa, 2017).

The atmospheric regions ionization condition is as follows containing their respective species.

- Thermosphere: contains positive ions and electrons.
- Mesosphere: contains positive and negative ions of small amount.
- Stratosphere and below: As shown in Figure 2.13 a, no free electrons present in this region.

Once the ions and electrons are produced by either of the two mechanisms, usually they would recombine again to a neutral particle in a very short time. Radiative recombination, dissociative recombination and charge exchange are the responsible chemical reactions of ion loss. Since atmospheric density decreases as altitude increases, collisions between the molecules, atoms and

free electrons become less frequent so that some of the ions can survive long enough that the ionosphere lasts through the night, especially at higher altitude. Therefore, the ionization process at any ionospheric region is a balance between the rate of ion production and ion recombination in that region of the ionosphere.

2.2.1 Ionospheric Regions

The dynamics and structure of the ionosphere are dependent on both spatial and temporal variations that can be periodic as well as irregular. Because of variation of relative ionization, loss and transport phenomena, the changes in the ionosphere are different at different altitudes. Therefore, Earth's ionosphere is divided into three regions. The regions are D, E and F getting their names on historical basis.

D Region

The D region of the ionosphere is the lowermost region of the ionosphere of the Earth that lies at an approximate altitude of 50-90 km with typical electron densities of around 10^8 - 10^9 m^{-3} . This region consists mostly of N_2 , O_2 , Ar, CO_2 , He, and a highly variable quantity of O_3 and H_2O with ionized components of NO^+ and O_2^+ . Solar X-ray, EUV and cosmic ray ionizes in the D region. Since the electron collision frequency in this region is high, radio wave absorption is quite significant. Like the other ionospheric regions, the electron density in the D region is subject to typical diurnal, seasonal and solar cycle variations.

E Region

The ionosphere from an altitude of 90-150 km is the E region with principal NO^+ and O_2^+ , and secondary O^+ and N_2^+ ion components. In the E region, ionization is mainly caused by X-rays and UV radiation. The electron density in this layer is 10^{10} - 10^{11} m^{-3} . It exhibits daily maximum at local noon, seasonal maximum in summer and solar cycle. The E region remains at night as a weakly ionized region of the ionosphere.

F Region

The F region is the most important ionospheric region which is used as a reflector in radio communications and navigation systems. It extends between 150 and 1000 km in altitude. Radiation from the Sun splits it into F1 and F2 regions. The F2 region is always present during the night. Therefore F1 and F2 regions merge a few hours after sunset and the F region is reshaped.

F1 Region

The F1 region of the ionosphere lies at an altitude of about 150-210 km solar activity, season and geomagnetic activity varying its height. The region has ionized components of NO^+ and O_2^+ as primary and O^+ and N^+ as secondary positive charge carriers. It is more pronounced in summer than in winter and always disappears during the night. Sometimes it disappears even in day time of the winter season. The electron density of the F1 region reaches about $2 \times 10^{11} \text{ m}^{-3}$ at midday. Its main source of ionization is extreme ultraviolet solar radiation.

F2 Region

The F2 region is the most important region of the ionosphere which is present 24 h a day under all solar-terrestrial conditions. In this region the dominant charge carriers are O^+ ions with secondary H^+ and He^+ , and the main electron-ion source is the process of photo-ionization by EUV radiation. It has a maximum electron density between 10^{10} and $8 \times 10^{12} \text{ m}^{-3}$. The rate of electron loss of the F2 region depends on the concentration of molecular ions of O^2 and N^2 , whereas the production rate depends on the concentration of atomic oxygen.

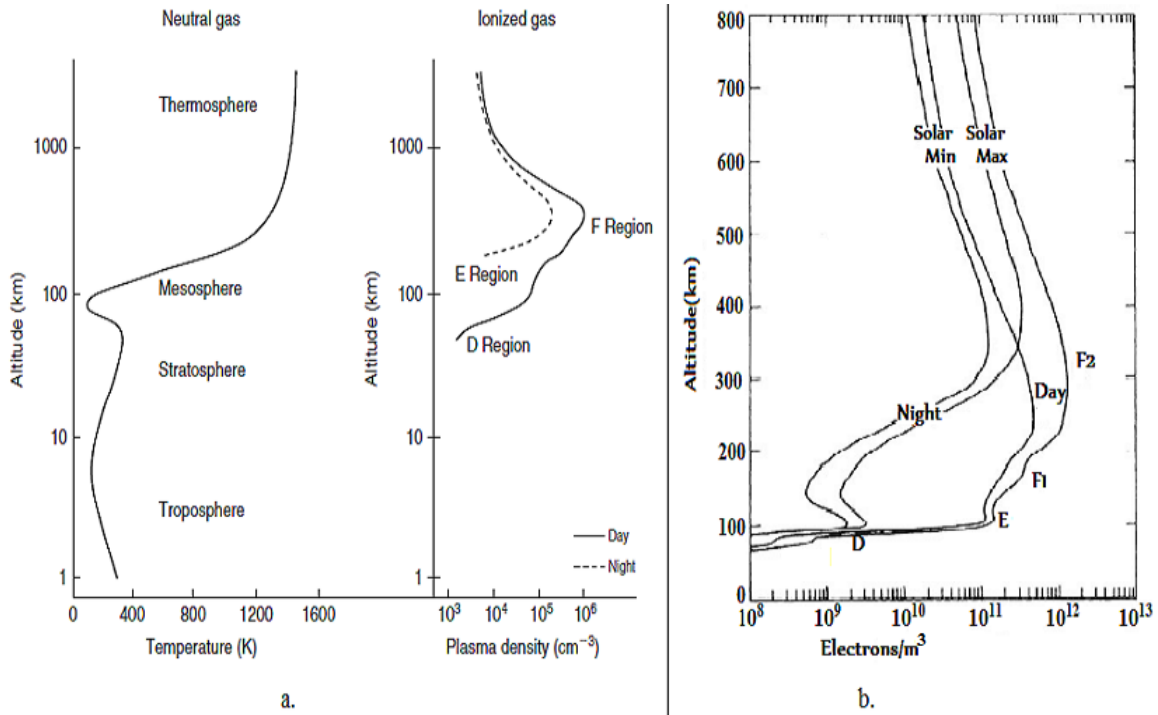


Figure 2.13: a. Height profile of the atmospheric temperature and the daytime and night-time ionospheric plasma density, (Kelley, 2009), b. Mid-latitude daytime and night-time ionospheric electron density profiles for sunspot maximum and minimum conditions, (Brekke, 2013).

In 1997 evidence was found for an F3 region to be present in the equatorial F region ionosphere (Zolesi & Cander, 2014). Experimental and theoretical investigations conducted on the presence of this region suggest that a combined effect of electrodynamic drift and neutral wind during morning to noon periods can drift an F2 layer upwards to form an F3 layer, while the usual photochemical and dynamic effects maintain a normal F2 layer at lower altitudes.

2.2.2 Polar Ionosphere

The polar regions are unique areas of the ionosphere as the daynight cycle of solar radiation has a strong seasonal dependence. Winter seasons are almost continuously dark while in summer, the Sun continuously radiates to the atmosphere. The other point that makes the polar region special is the close connection to the near-space environment due to the nearly vertical magnetic field that results an additional ionization source with the aurora. Unlike the lower latitude ionospheric region variations, which are mostly dominated by the rotation of the Earth, the high latitude regions' ionosphere is highly variable due to the changing conditions in the solar wind.

The polar ionospheric region is divided into three regions. They are the polar cap, the polar oval and subpolar latitudes. The polar caps are circular areas surrounding the magnetic poles with a typical diameter of about 30° and have nearly vertical magnetic fields. They are poleward of the auroral oval in the Northern and Southern Hemispheres. The polar/auroral oval is an annular region surrounding the polar cap of a few degrees in latitudinal width. The magnetic field lines in auroral oval either connect to the solar wind or lead back to the other hemisphere. The regions immediately adjacent to the auroral ovals when we move equatorward are the subpolar

latitudes. The polar ionosphere is closely connected to the solar wind due to its magnetic field. Consequently, when particularly violent events on the Sun inject high-energy protons into the solar wind, these energetic protons can be guided by the Earth's magnetic field directly into the polar ionosphere. Since the protons have enough momentum and energy, they penetrate deep into the atmosphere and cause significant ionization.

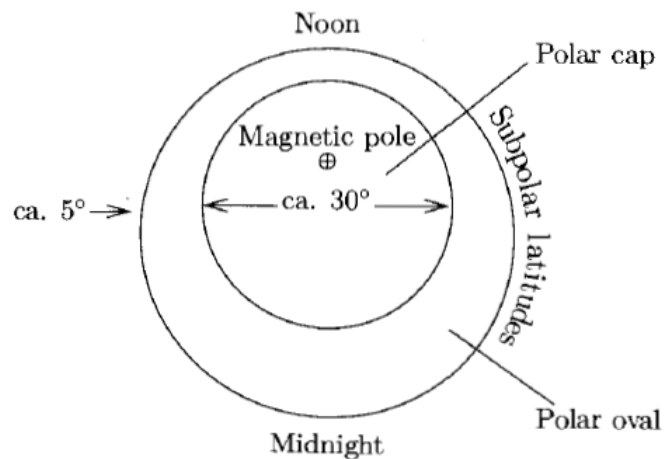


Figure 2.14: Topology of the polar ionosphere, (Prölss, 2004).

2.2.3 Radio Wave Propagation in the Ionosphere

A radio wave transmitted into ionized regions is always bent. This is due to velocity variation of the propagating wave when it enters a region of different charged ion density. As it is shown in Figure 2.15, when the radio wave enters the denser region, its upper portion moves faster than its lower portion. The abrupt speed increment of the upper part of the wave causes it to bend back toward the Earth. The refraction of the transmitted wave is always toward the propagation medium where the velocity of the radio wave is the least.

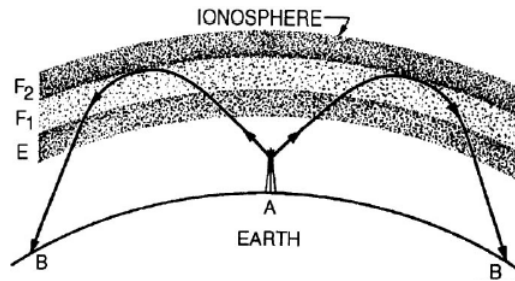


Figure 2.15: Radio wave refraction in an ionized region, (Simmons & Ace, 1995).

The degree of refraction of a radio wave depends on three main factors: the *ionization density* of the layer, the *frequency* of the radio wave and the *angle* at which the radio wave enters the layer.

Ionization Layer Density

When a radio wave enters a region of increasing ionization, the velocity of the wave increases resulting it to refract back toward the Earth. As it can be seen from Figure 2.16, in the highly dense middle region, refraction occurs more slowly since the ionization density is uniform. When the wave enters the upper less dense region, the velocity of its upper part decreases and it is bent away from the Earth.

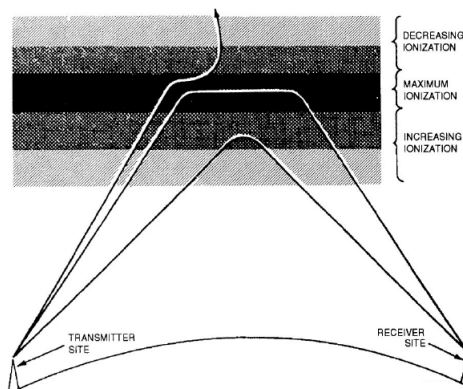


Figure 2.16: Effects of ionospheric density on radio waves, (Simmons & Ace, 1995).

Frequency

Lower frequency radio waves are refracted more rapidly by a given degree of ionization. In Figure 2.17 three radio waves of differing frequencies are entering the same ionospheric layer at the same angle. The figure shows that the 5-MHz wave is refracted quite sharply, while the 20-MHz wave is refracted less sharply and returns to Earth at a greater distance than the 5-MHz wave while the 100-MHz wave is lost penetrating the ionized region.

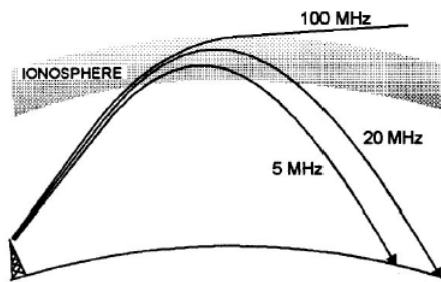


Figure 2.17: Frequency dependence of radio wave refraction, (Simmons & Ace, 1995).

Angle of Incidence

When a radio wave enters a layer of the ionosphere and returns back to the Earth, the angle of reflection is roughly equal to its angle of incidence. As shown by Figure 2.18, three radio waves of the same frequency are entering the same layer at different incidence angles. They are refracted differently though having the same frequency and propagating the same ionized layer. This is due to the difference in their incident angles. A radio wave of specific frequency at a given ionized layer will have a unique angle called critical angle. Any radio propagation, at a given frequency, that leaves the antenna at an incidence angle greater than this angle will be lost into space. Waves

that leave the antenna at smaller angles than the critical angle be refracted and be returned to Earth. The critical angle of radio waves depends on layer density and wavelength of the signal.

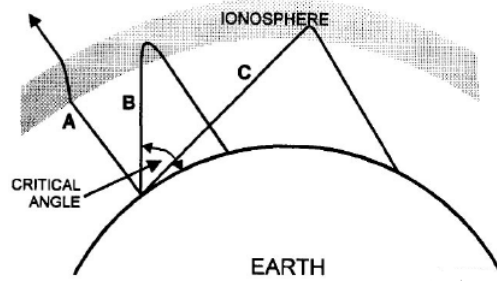


Figure 2.18: Incidence angle dependence of radio wave refraction, (Simmons & Ace, 1995).

2.2.4 Variability of the Ionosphere and Ionospheric Storms

Ionosphere is a highly changing environment both spatially and temporally (Tebabal *et al.*, 2018). Variation of the solar radiation and ejection that are erupted to our planet Earth at very different time scales are the main elements of ionospheric variability and storms. The solar radiation and ejection variabilities are resulted due to variable and periodic solar activities and solar-Earth system. The former includes cycles of 27 days, 11 years, 22 years, 88 years (Gleissberg cycle) and 205 years (de Vries cycle) which are average time scale solar activity cycles whereas the latter includes daily and seasonal variations.

Sudden changes in the solar activity such as solar flares induce a series of disturbances in the ionosphere driven by a magnetic storm which again results sudden variations in the ionosphere (Maruyama *et al.*, 2009). This event is called *ionospheric storm*. In an ionospheric storm, when the electron density is enhanced it is called a *positive storm* and when the electron density is

decreased we call it a *negative storm*. Ionospheric storms have big impacts on radio communications. In the next sections solar flares, travelling ionospheric disturbances (TIDs) and coronal mass ejections, which are triggers of ionospheric storms, will be discussed.

2.2.5 Geomagnetic Storms

Geomagnetic storms are realistic threats to the world's electrical power grids, telecommunication systems and global satellite navigation networks. They are the major disturbances of the Earth's magnetosphere that occur when the interplanetary magnetic field (IMF) turns southward and remains so for a prolonged period of time (Verma *et al.*, 2009). At geomagnetic storm events, the solar wind will have sudden strong variations in the speed and density due to coronal mass ejections that disturb the Earth's magnetosphere. This southward IMF results effective conditions for energy transfer from the solar wind to the Earth's magnetosphere.

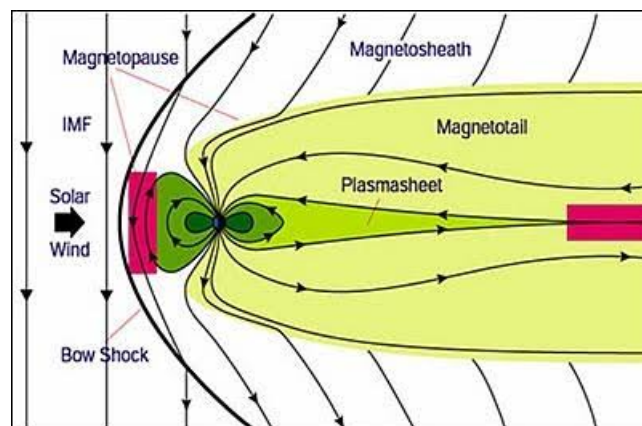


Figure 2.19: Schematic view of magnetic field of the Earth, (SwRI).

Since the solar phenomena are very complex, geomagnetic storms exhibit great variability and complexity. Nevertheless, a classic storm features of which are frequently observed has three phases (Jursa, 1985). The first phase is the **initial phase** with sudden commencement both resulting from change in compression of the magnetosphere following a passage of discontinuity. The initial phase lasts two to eight hours with the field remained compressed by the increased solar wind pressure. The second phase is the **main phase**. It results from an inflation of magnetosphere by ring current due to the previous southward IMF which permitted energy extraction from the solar wind. Rapid depression in horizontal (H) component of the magnetic field is observed in the main phase. The final phase is the **recovery phase**. It is a quiet increase of the field to the prestorm level resulted from the decrease in the ring current plasma as the source terminates and the existing plasma is lost by different mechanisms. A recovery phase has a characteristic time about one day but can be much longer which is faster at first.

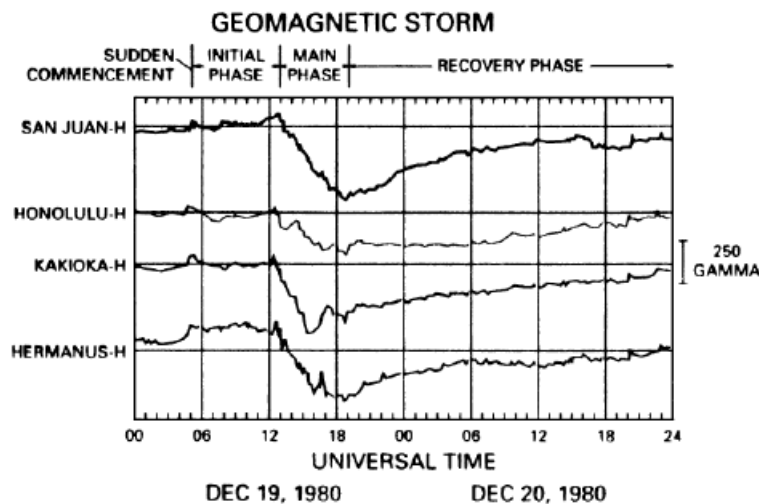


Figure 2.20: H component field variation at four observatories, (Campbell, 2003).

Depending on their auroral activities, geomagnetic storms are categorized using their K_p values. K_p values 0 up to 3 imply that there is very little geomagnetic activity, and a value of 9 implies an extreme geomagnetic storm. The category is shown in Table 2.1.

Table 2.1: Categories of Geomagnetic Storms.

K_p	G-Scale	Auroral Activity
0-3	G0	Quiet
4	G0	Active
5	G1	Minor Storm
6	G2	Moderate Storm
7	G3	Strong Storm
8	G4	Severe Storm
9	G5	Extreme Storm

2.2.5.1 Solar Flares

Solar flares are natural phenomena that are erupted outwards into space from the Sun by releasing massive amount of energy that ranges to about 10^{25} J. It is a strongly localized ($\lesssim 0.1 R_S$) and short-duration ($\lesssim 1$ h) release of that great amount of energy in the solar atmosphere (Pröls, 2004). Solar flares reach us first in the form of electromagnetic radiation affecting vulnerable regions by suddenly brightening them and becoming detectable in various wavelength ranges. Even though the physics behind solar flares remains inadequately understood, the energy that

gets released during a solar flare is a result of spontaneous reconnection by which magnetic energy is converted into the kinetic energy of the particles.

In a magnetic flux tube from the Sun that extends out into the corona, the reconnection process leads to a strong acceleration of charged particles at the apex of this flux tube leading the particles to be injected on their helical trajectories into the chromosphere. As the electrons strike the denser gases of the chromosphere, they are decelerated by collisions and produce emission that lies in the EUV and X-ray range, particularly in the hard X-ray range, resulting a rapid increase in the short wavelength emission while the precipitating protons at energies of several 10 MeV can stimulate nuclear emission in the γ range or at higher energies release neutrons and positrons.

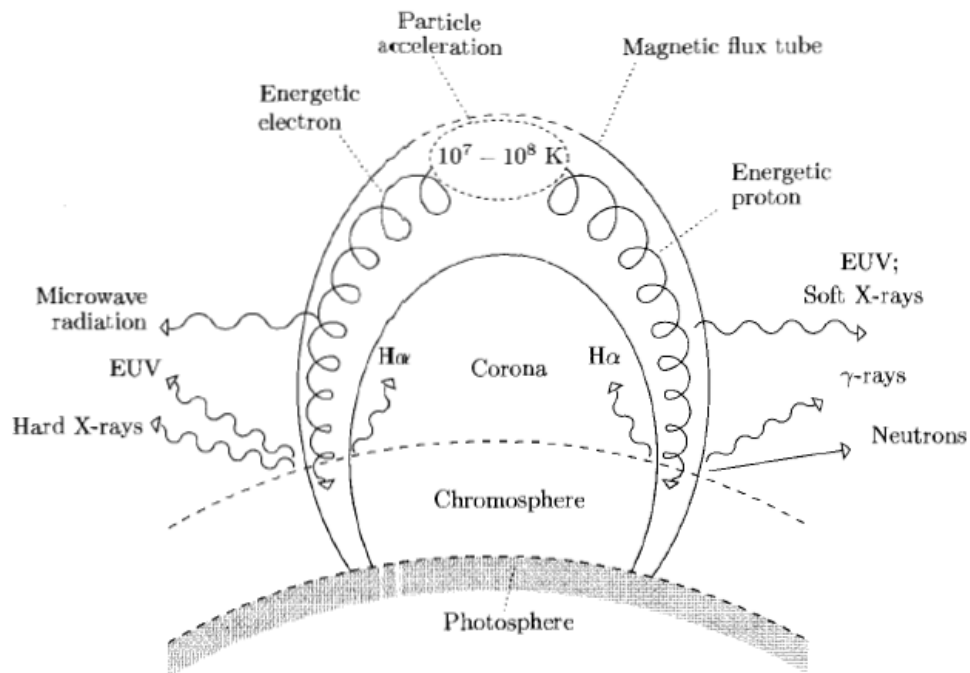


Figure 2.21: Possible source location of the various solar flare emission ranges, (Prölss, 2004).

The incident energetic particles in the chromosphere are thermalized as a result this there will be strong ionization and heating of the resident gases. This again leads the outer layer of the chromosphere to be evaporated as a plasma into the coronal extension of the flux tube. Then, the hot plasma of the apex region heats the adjacent lower-lying regions so that eventually the entire flux tube is filled with a completely ionized hot gas at a temperature of 10 to 100 million K. The long lasting increase of the EUV and soft X-ray radiation following the impulsive phase of the flare emission is due to the thermal bremsstrahlung of this plasma.

The emission of H_α radiation might be due to two processes; either by direct excitation of the chromospheric Hydrogen from the thermalization of incident energetic particles or by emission stimulated from the recombination of collisionally ionized Hydrogen.

The energy released by the solar flare accelerates particles not only downward in the direction of the denser solar atmosphere, but also into interplanetary space along magnetic field lines that have been opened by the reconnection process (Pröls, 2004). These particle beams stimulate the background plasma of the corona to undergo oscillations at the local plasma frequency that is recorded at the Earth in the form of radio emission.

The solar flares induce modest disturbances to the Earth. The disturbances are consisting essentially of the additional ionization produced by the EUV and X-ray emission, but also by energetic particles. The rapid increase in the ionization density (sudden ionospheric disturbance, SID) leads to an abrupt change in the reflection conditions for radio waves (Pröls, 2004). The EUV radiation creates additional ionization in the E and F regions of the ionosphere while the hard X-

ray emission increases the electron density in the D region that leads to short-term attenuation of the radio waves. The whole process increases the conductivity of the ionosphere triggering a sudden intensification of the ionospheric currents and their associated magnetic field disturbances. In a flare, solar radiation affects the dayside of the Earth's upper atmosphere while energetic protons and electrons only have access to the polar upper atmosphere. But since high energy protons behave like cosmic rays and their gyroradii are so large, they can penetrate easily into the magnetosphere at mid-latitudes.

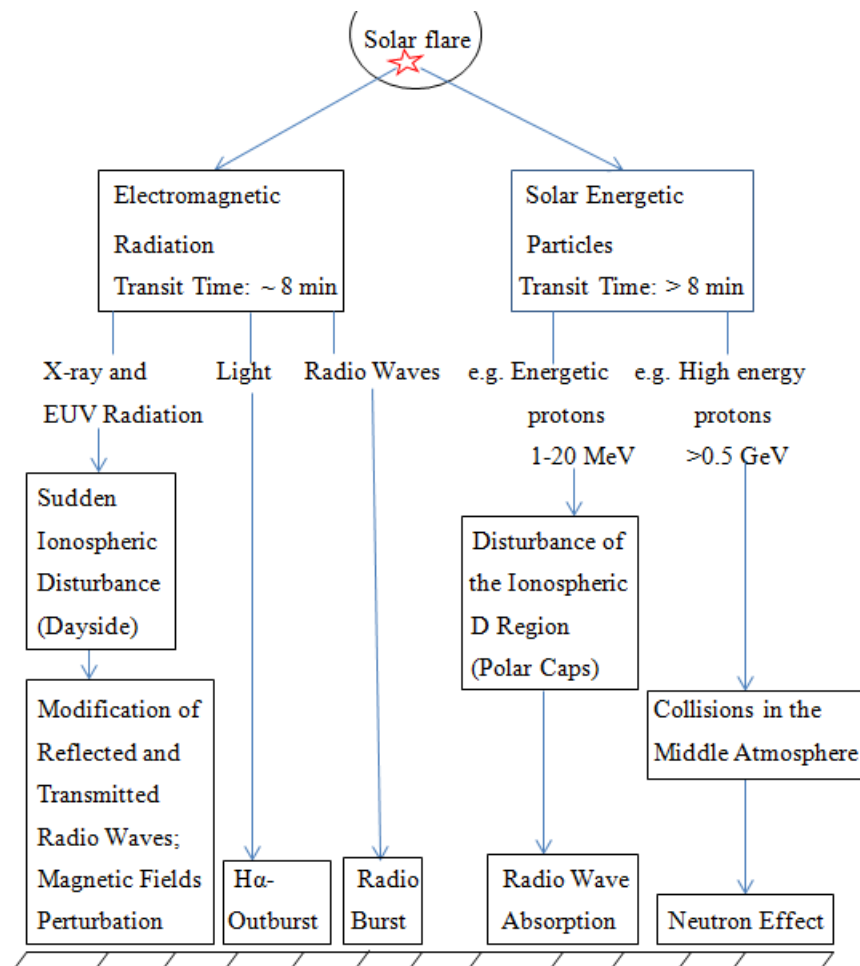


Figure 2.22: Solar flare effects on the Earth, Adapted from (Pröls, 2004).

Solar Flare Classifications

The classification of solar flares is based on their X-ray outputs. Flares are classified according to the order of magnitude of the peak burst intensity is measured at the Earth and used to classify solar flares according to the order of this measured peak magnitude. The X-ray out puts are in the 0.1 to 0.8 nm wavelength band. Accordingly, flares are classified into five main divisions as follows.

Table 2.2: Solar flare classes measured as the peak is 1-8 Angstrom band.

Solar Flare Class	Intensity (Wm^{-2})
A	$I < 10^{-7}$
B	$10^{-7} \leq I < 10^{-6}$
C	$10^{-6} \leq I < 10^{-5}$
M	$10^{-5} \leq I < 10^{-4}$
X	$I > 10^{-4}$

All the solar flare classes have nine subdivisions that range from 1 up to 9, i.e., B1 to B9 or M1 to M9. The multipliers in each subdivision are used to indicate the level within each class. By this expression, M7 implies $7 \times 10^{-5} \text{ Wm}^{-2}$.

2.2.5.2 Coronal Mass Ejections

The corona of the solar atmosphere is structured by strong magnetic fields where these fields are closed, the confined solar atmosphere can suddenly and violently release bubbles of gas and

magnetic fields into the heliosphere. These large expulsions of plasma and magnetic fields are coronal mass ejections (CMEs) which are widely recognized as being responsible to generate measurable disturbances in solar wind plasma parameters and geomagnetic storms in the magnetosphere of the Earth (Verma *et al.*, 2009). Originally, CMEs were termed coronal transients. They are sometimes associated with solar flares but they can occur independently.

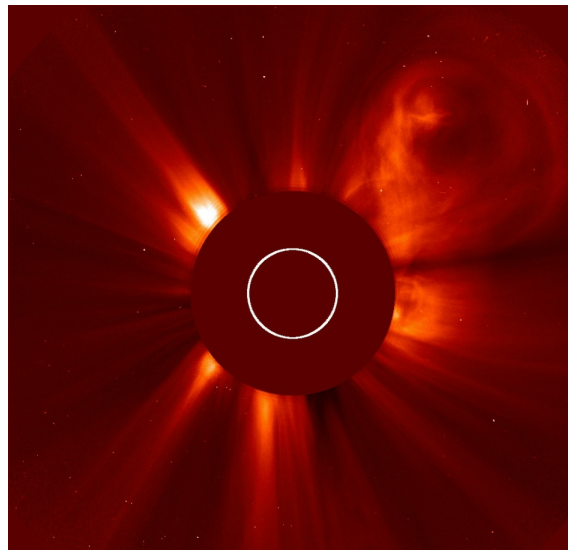


Figure 2.23: Phenomenon of Coronal Mass Ejection, (NASA).

A large CME can contain a billion tons of coronal matter and carry an embedded that is stronger than the background solar wind interplanetary magnetic field strength. CMEs from the corona can be accelerated from 250-3000 kilometers per second ,i.e, several million kilometers per hour in a spectacular explosion. Faster Earth-directed CMEs can reach the Earth in 15-18 hours while the slowest one can take several days. A typical large CME can have a size quarter of the space between the Earth and the Sun by the time it arrives. The expelled out solar materials that stream through the interplanetary medium impact any planet or spacecraft in their paths.

2.2.5.3 Travelling Ionospheric Disturbances

Travelling ionospheric disturbances (TIDS) are common feature of the ionosphere which are wave like fluctuations of the electron density induced by gravity waves in the neutral atmosphere (Afraimovich *et al.*, 2001; Francis, 1974), and have been widely studied over the last decades (Hajkowicz, 1990; Kotake *et al.*, 2007; Ding *et al.*, 2007). Their occurrence and direction of travel show significant diurnal, seasonal and sunspot cycle variations (Zolesi & Cander, 2014). Travelling ionospheric disturbances are classified into two classes. They are medium-scale TIDs and large-scale TIDs.

Medium-scale TIDs (MS TIDs) and large-scale TIDs (LS TIDs) are distinguished by authors Zolesi & Cander (2014), Francis (1974), Hajkowicz (1990) and Hernandez-Pajares *et al.* (2006) that MS TIDs have shorter periods of 10 min to 1 h and a wavelength of up to 300 km, moving more slowly with speed range 50-300 m/s while LS TIDs have a period of 1-3 h and a horizontal wavelength of 1000-4000 km moving faster than 300 m/s. The MS TIDs are related to meteorological phenomena like neutral winds whereas the generation regions of LS TIDs are located in the auroral areas of the northern and southern hemispheres. The MS TIDs propagate either equatorwards from the auroral ionosphere or upwards from the lower atmosphere or away from the equator while the LS TIDs propagate from the auroral ionosphere of both hemispheres towards the equator (Francis, 1974).

CHAPTER 3

Instrumentation and Data Analysis

3.1 Stanford Solar Center's SuperSID Monitor

The SuperSID Monitors are inexpensive space weather monitors that are developed by Stanford University's Solar Center to be installed and used to detect changes to the Earth's ionosphere caused by solar flares and sunrise to sunset changes. In other words, they are used to monitor the ionosphere for Sudden Ionospheric Disturbances (SIDs) and Sudden Enhancement of Signals (SEs) using the signal from transmitters situated around the world which nations use to communicate with their submarines (Arnold, 2014). They are small in size with 80 millimeters diameter (See Figure 3.1).

A SuperSID receiver has two cables: The jack cable in Figure 3.1 is plugged into the AUDIO INPUT port on the computer or on the sound card whereas cable 2 of the receiver is plugged into the USB port on our computer for power supply. It requires a short length of RG-58 50 ohm coaxial cable to connect the SuperSID receiver and its built antenna. A minimum of 120 m antenna wire is also needed to make the antenna. A 22 AWG (American Wire Gauge) wire is a proposed wire type to build the antenna. Once the monitor begins running no further input is needed, apart from checking the data for evidence of solar activity The condition of the antenna



Figure 3.1: The Super SID Receiver

must be also checked every now and then, especially if it is placed outdoor.

Everyday observation of the Sun using the SuperSID monitor leads to notice monthly and seasonal changes in the ionosphere. (Arnold, 2014) recommended the 2013-2018 year interval would be an excellent time to purchase a SuperSID monitor as the Sun was building up to the solar maximum again, and between these years the Sun should be producing some useful data despite the Sun can throw out like a massive X-ray flare during solar minimum.

3.2 Working Principle of the SuperSID Monitor

Many powerful transmitters that are used by different countries to communicate with their submarines are situated around the globe. The longer wavelength signals from the transmitting stations have the ability to penetrate objects such as the deepest oceans of the world. They can also travel around the Earth bouncing off the ionosphere. The SuperSID monitor picks up these

bouncing signals through its antenna. The aim of the receiving loop antenna which is a winding of copper wire around a frame is to convert an electromagnetic wave into a voltage. Fundamentally, it is an LC (inductor capacitor) circuit in which the inductor concentrates and stores magnetic energy while the capacitor concentrates charge and thereby stores electric energy. The inductance is formed by the wire loop and the capacitance is formed by the wiring metal surface running in parallel along the loop.

The output voltage of the loop antennas is proportional to the field of the transmitted signal. Their performance is dependent on the number of turns and the area of each loop. The following two equations show the dependence of voltage appearing between the terminals of the antenna.

$$V = 2\pi\mu_0 NfAH\cos\theta \quad (3.1)$$

$$V = 2\pi\sqrt{\mu_0\epsilon_0} NfAE\cos\theta \quad (3.2)$$

where μ_0 is the permeability of free space, ϵ_0 is the permittivity of free space, N is the number of turns, f is the frequency of the signal, H is the magnetic field intensity of the incident radio signal, E is the electric field intensity of the incident radio signal and θ is the angle the flux lines make with the loop axis.

The signal picked up by the antenna is guided to the preamp of the monitor by the coaxial cable. Then, as the name indicates, the preamp amplifies the signal before it reaches the sound card. The sound card converts the signal from analog to digital. Finally, the program installed and running on our computer tracks the signal strengths and processes the data. For instance, if there is any

change in the ionosphere because of a solar flare from the Sun and solar radiation variation, this event can cause a sudden increase or drop in the signal strength. So the SuperSID monitor will pick up this change in signal strength between the observer's local sunrise and sunset times, as the ionization in the D layer is lost at night (Arnold, 2014). This instrument enables to monitor six different transmitters simultaneously and it takes a reading every 5 seconds throughout the day. At the end of a day, all the data is saved by the the software program itself. Using this software a graph can be produced and the graph can then be examined for traces of solar activity.

3.3 Constructing a SuperSID Loop Antenna

The SuperSID monitor antenna is a simple wire wound antenna that can be made from a variety of materials such as wood, PVC or from both materials. It is frame that holds up wraps wire. The antenna doesn't have a standard size or shape. One can either build a small antenna that is about 1 meter wide with lots of wraps of wire, or a large antenna of width 2 or more meters with fewer wraps, or something in between. Smaller antennas are easier to build but require more wire to pick up the signal and are less sensitive. But larger antennas are more sensitive though they are difficult to carry around and mount outside because of wind, rain and space requirements. The larger in diameter, the better the antenna will be.

3.3.1 Antenna Materials

To make a SuperSID antenna, we need the following materials.

- About 120 meters of insulated 24 AWG wire
- RG-58 Coax Cable of sufficient length to attach our antenna to our computer.



Figure 3.2: Antenna Wire (Yellow) and Coaxial Cable (Black).

- BNC connector
- Four terminal connectors, a BNC (Bayonet Neill-Concelman) connector and a terminal block (1, 2 and 3 in Figure 3.3 respectively).

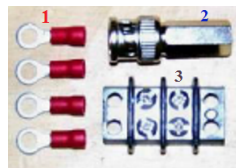


Figure 3.3: Antenna Fittings

- Wooden sticks



Figure 3.4: Wooden Sticks for Making an Antenna Frame, (Scherrer *et al.*, 2015)

- Nails, screws, glue or whatever material that is appropriate for this purpose can be used.

- Antenna Stands



Figure 3.5: Sample SuperSID antenna stands

3.3.2 Antenna Assembly and Packaging

- **Winding the Antenna:** It requires a minimum of two people but three or four is better. If there only two, one person checks the wire gets wound correctly while the other feeds the spool of wire. But if three or four individuals are available, then one can feed the wire, the second turn the antenna frame and the third person make sure that the wire is tightly tensioned around the antenna frame. The fourth person can count the number of turns.

We start winding on one side of the antenna stringing out the wire from the center to one of the ends of the antenna frame leaving enough slack on the end to eventually attach it to the terminal block. It is better to connect a terminal connector to this end of the wire before winding begins. While winding the antenna wire, we need to keep tension on the wire. The person holding the spool has to make sure the wire is feeding properly and the person winding the antenna cleverly checks that the wires are neatly going around in each of the slots. We will do about fifty turns on a small size antenna and 25 on a large antenna. We leave a little slack to the last turn too for connecting the antenna wire ends with the



Figure 3.6: Pictured while my classmates were assisting us in winding the antenna, right to left: Yamrot Biniyam, Addisalem Mollawork and Dasash Maregu.

terminal block after a terminal connector is connected to it. Finally, we wrap an electrical tape on the frame to hold the wire ends and to protect them from coming undone.

We attach a terminal block at the jointing box of the antenna frame. The terminal block is used to connect the antenna wire ends to the two terminals of one end of the coaxial cable. On the other end of the coax is a BNC connector that will be connected to the preamp. If the terminal connectors and the BNC were not connected with the wire and the coaxial cable before getting the SuperSID monitor package, the next procedure explains how to prepare the coax.

First we strip off the outer insulation of the cable about 2 inches with sharp pocket knife. We have to be cautious not to damage the braiding below. Then we untangle the braiding using a small

screw driver or a similar material. Twisting it together we form a single wire. Next, we strip the center conductor carefully back about half an inch. To make the attachment to the terminal block, crimp or solder the two terminals of the coax to two spade connectors. Figure 3.7 shows the numbered steps of the procedure.

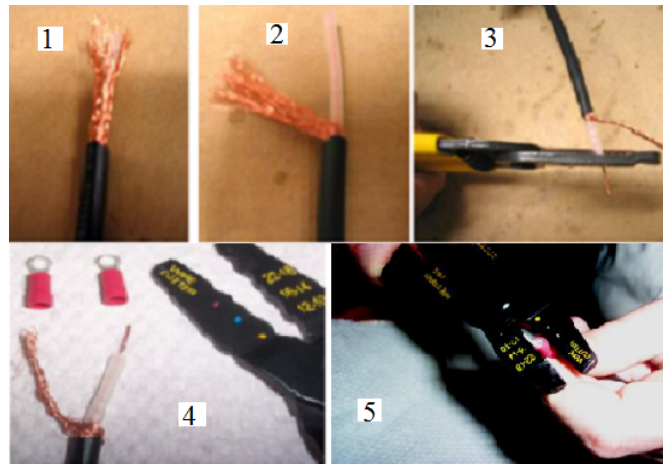


Figure 3.7: Stripping and connecting a Coaxial Cable, (Scherrer *et al.*, 2015)

Then we attach the spade connected coax wires to the terminal block. To do this we unscrew the two screws on the opposite side of the connected antenna wires. Next, we slip the spade over the screw and tighten back down as seen in Figure 3.8.

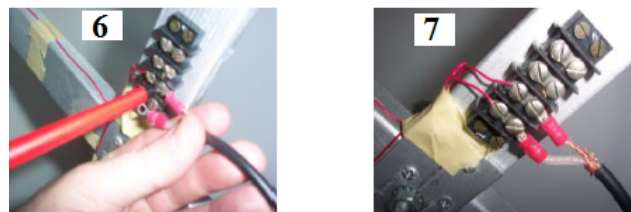


Figure 3.8: Connecting Spades to the Terminal Block, (Scherrer *et al.*, 2015)

On the other end of the coaxial cable, we connect the BNC connector which is going to mate with

our SuperSID receiver. So we start by stripping off about 21 mm of the outer insulation carefully not to damage the sheathing. Then we cut the braiding in way that it sticks out about 6.35 mm from the covered coax. Next, we strip the center conductor about 14.3 mm. We make sure that it has no stray wires. If any, we have to twist it together.

The next task is to place the center conductor into the hole in the BNC connector and twist the shaft in a clockwise direction until the screws are tight enough and make it cover any exposed ground wire. After that we need to wrap an electrical tape around the spot where the BNC connector meets the antenna cables outer insulation. Now we can connect our antenna with the receiver for the required purpose. Figure 3.9 is a figurative description of the procedure.

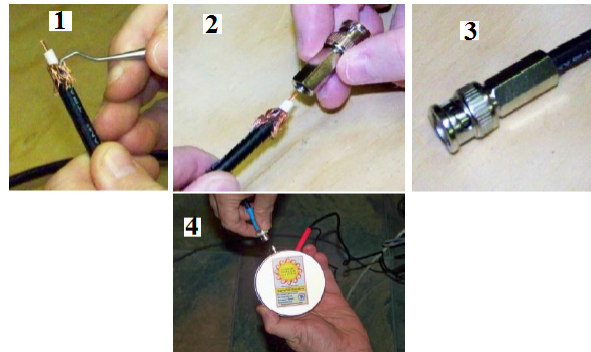


Figure 3.9: Stripping Coax for BNC connector, ([Scherrer *et al.*, 2015](#))

3.3.3 Antenna Site Selection

Our antenna is made ready to do its task. Therefore, it must be located somewhere appropriate for its better performance. Since the signals that our antenna picks up are very small, we have to locate it in an area which is relatively free of electric interference. We can place it indoors

or out. What must be noted is, the place should be away from interference sources as much as possible. Generators and other large electric equipments, power lines, large metal-framed buildings, microwave ovens and others are some interference sources. Since a SuperSID antenna works at ground level, it doesn't have to be high up to protect it from lightning strike. The monitor and computer has to be relatively nearby in a place that can be secured from being tampered with, such as a lockable closet with access to power, and internet connection if possible.

3.3.4 Sound Cards and Software Installation

3.3.4.1 Sound Cards

The sound cards can be designed either in a way that they are inserted to our computers or in a USB type. Figure 3.10 shows the two types of the sound cards. They have function of detecting the information within the input signal and processing it into a useful information that the operating program can use and store digitally. The properties of the sound card in our computers can be displayed by clicking on my computer tab then the open control panel tab, and selecting and hitting the audio manager tab.



Figure 3.10: Sound cards to convert analog signals into digital , (Scherrer *et al.*, 2015)

3.3.4.2 Software Installation

We got the SuperSID monitor with its own operating program on a CD-ROM. After collecting information about our site, its location, the monitor ID, sampling rate of our sound card and the time zone of the place we live, we install the software. Then the information is filled and all the monitor components will be connected. Finally, the sound card set up is conducted accordingly and we run the program to collect data. For further information of the procedure Scherrer *et al.* (2015) can be referred, which is the SuperSID manual.

3.4 Data Source

The interest of this thesis work is to study the variability of the ionosphere due to solar activities. Many researchers use different techniques to investigate these solar phenomena. In this work we used two different data sources to investigate the ionospheric variability. One type of data we used a SuperSID monitor data. For this purpose, we deployed a typical sudden ionospheric disturbance monitor (type SuperSID) at Bahir Dar, Ethiopia (11.6° N, 37.4° E) after building its rectangular loop antenna. The SuperSID monitor picks up and tracks very low frequency (VLF) radio signal transmissions around the globe. Monitoring radio transmissions enables to monitor ionospheric variability as the transmission is subject to events in the ionosphere.

The other data type we use in this work is a Swarm Satellite electron density data. Using this data, the response of the top ionosphere to geomagnetic storms will be analysed. The data is downloaded from ftp://swarm-diss.eo.esa.int/Advanced/Plasma_Data/.

3.5 Data Analysis

3.5.1 Data Analysis of SuperSID Monitor Data

In this work a large sized wooden block antenna was built with 24 AWG antenna wire after attempting to pick up radio signals using two different small sized antennas. Figures 3.11 and 3.12 show our three antennas built for the SuperSID VLF receiver.



Figure 3.11: VLF antennas built for a SuperSID Monitor.

After the antenna construction, we conducted the software installation and configuration accordingly. Next, we conducted the hardware and software collection together. The following steps



Figure 3.12: The large VLF antenna we constructed for our monitor: Picture, me with my thesis advisor Dr. Melessew Nigussie (Right).

are procedures how to set up and process the SuperSID data.

1. We plug a coax cable from the antenna into the antenna input on the SID monitor.
2. We plug the SuperSID Jack cable into the AUDIO INPUT port on a sound card. The USB of the sound card and the SuperSID power cable are plugged into the computer. Then we run the program and open the main window of the SuperSID application. The window looks like:

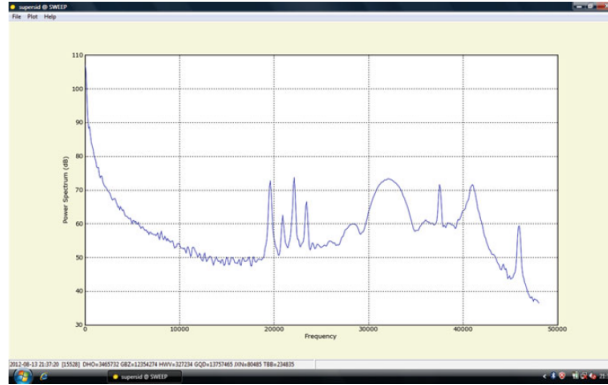


Figure 3.13: SuperSID application window with usable stations, (Arnold, 2014).

3. The program collects and saves the data every 24 hour. Using a complete 24 hour data we test the proper functioning of the monitor. If the plot of this 24 hour data shows the sunset and sunrise signatures, which are sharp rising and dropping of the radio signal strength respectively, we can be sure that we picked up and collected the necessary data. But the data can be still vulnerable to interference.

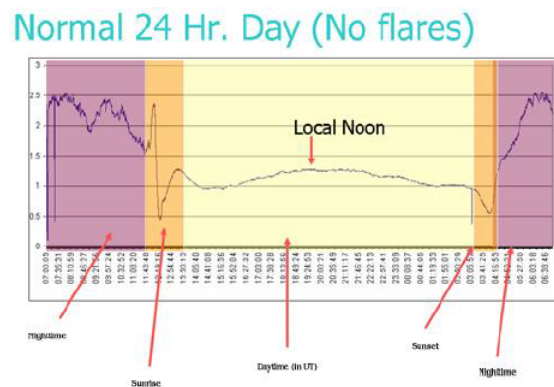


Figure 3.14: Sunrise and sunset signatures, (Scherrer *et al.*, 2015).

4. If there were solar flares our plot shows a very characteristic shape which is a swift increase in signal strength followed by a slower decrease. So we do identification of this events from

our plot. Figure 3.14 shows four solar flares.

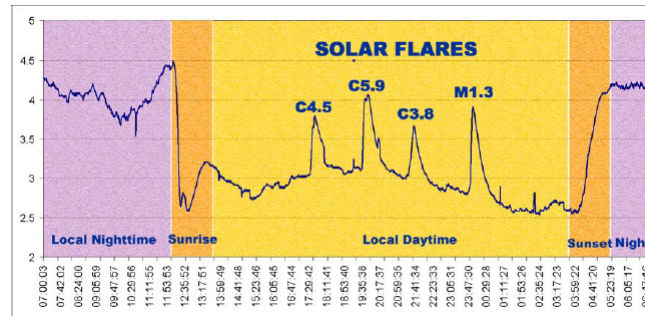


Figure 3.15: C and M class flares, (Scherrer *et al.*, 2015).

5. To compare our potential solar flare, one can use GOES satellite data from the internet. A sample GOES graph is shown in Figure 3.15. The red plot is used to compare solar flares.

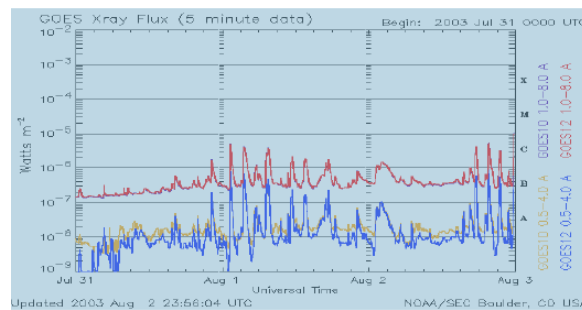


Figure 3.16: Data from different channels and different GOES satellites, (Scherrer *et al.*, 2015).

6. A solar flare can be tracked to its source on the Sun. Using the <http://sohowww.nascom.nasa.gov/> URL and hitting "Sunspots" the region numbers can be seen and identified on the Sun. Then the progress of active regions on the Sun can be watched and prediction of which groups might generate what size of flares can be tried. Using the SuperSID monitor the predictions can be tracked.

3.5.2 Data Analysis of Swarm Constellation Data

To analyse the Swarm satellite electron density (N_e), we develop a matlab program code. Then the data is imported electron density vs latitude and longitude graphs will be plotted for each orbit of the satellite on the storm day. Since the satellite passes through the dayside and the nightside of the Earth in each single full orbit (shown in Figure 3.17), both sides are investigated separately as the processes are different in the two sides. Using these outputs, we analyse the results of electron density variations in different sectors as a response of the geomagnetic storm event. The responses can be either positive or negative enhancing or suppressing the electron density.

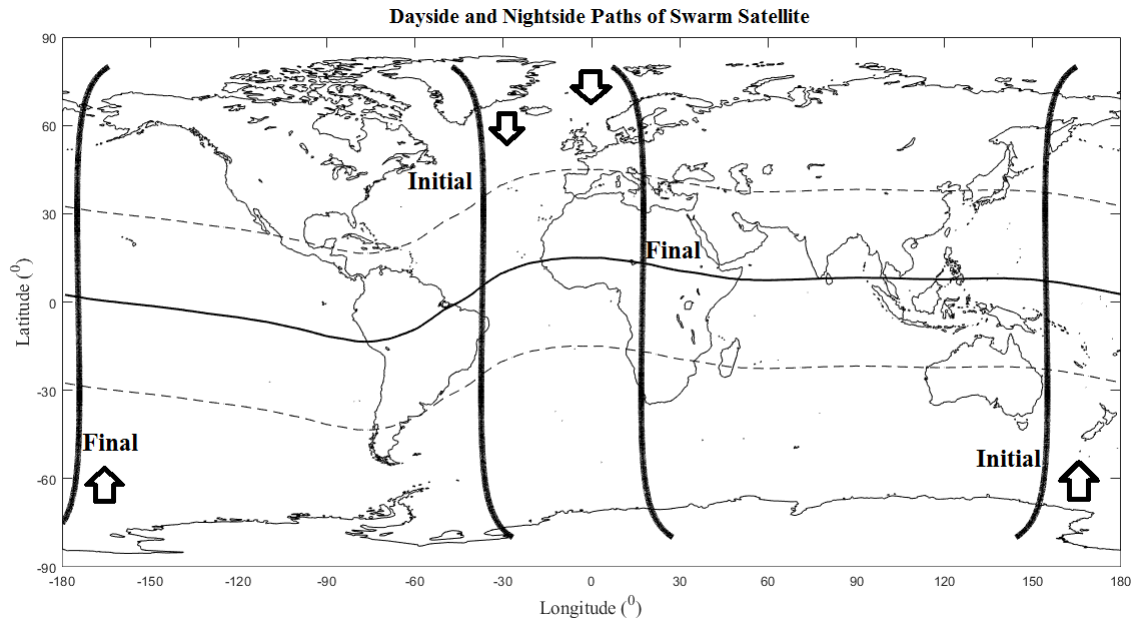


Figure 3.17: Dayside and Nightside Paths of Swarm Satellite.

To investigate travelling ionospheric disturbances (TIDS), we use a quiet day electron density data measured in that storm month at nearly equal local time. We subtract the quiet day electron

density data from the storm day data to remove the background data and see only the storm effect on the ionosphere as follows.

$$N_{ed} = N_{es} - N_{eq} \quad (3.3)$$

where N_{ed} is the electron density difference between the storm day measurement (N_{es}) and the quiet day measurement (N_{eq}). Then we will have contour plots of longitude, latitude and electron density difference between the storm day and the quiet day. Then the results will be analysed.

CHAPTER 4

Results and Discussions

4.1 Introduction

A SuperSID sudden ionospheric disturbance monitor is deployed after building its VLF antenna, and the top ionospheric response to an intense geomagnetic storm is investigated using Swarm satellite in situ data. Using the SuperSID monitor, different VLF radio transmissions are picked up and ionospheric variability during the day and night times is tracked inferring from the radio signal strength variations. This ionospheric variability is observed as a sudden rise of the radio transmission during sunset and as a sudden drop during sunrise.

Besides, by using electron density data from Swarm satellite, the top ionospheric region response to the 22-23 June, 2015 intense geomagnetic storm is discussed. We investigate the evolution of the storm from its initial phase to its recovery phase and the alteration of the ionosphere at different sectors of the globe. We will also report the possible drivers of the observed alterations. Moreover, we will state about the chance of a Swarm satellite to track both medium-scale and large-scale travelling ionospheric disturbances (TIDs).

4.2 SuperSID Monitor Deployment and Data Interpretation

We have constructed three antennas in our attempt to pick up VLF radio signals from Submarine stations around the world. The first was about 1 meter frame small antenna. This antenna didn't enable us to pick up radio transmissions. Plots of collected data using this antenna didn't show sunrise and sunset signatures which are sudden drop and rise radio signal strengths respectively. Therefore, we constructed an other medium size VLF antenna. Using this antenna we resolved the above two problems. Figure 4.1 shows sample plots of VLF radio signals as vertical spikes in two different sites. This appears when we run the installed program and pick up the signals.

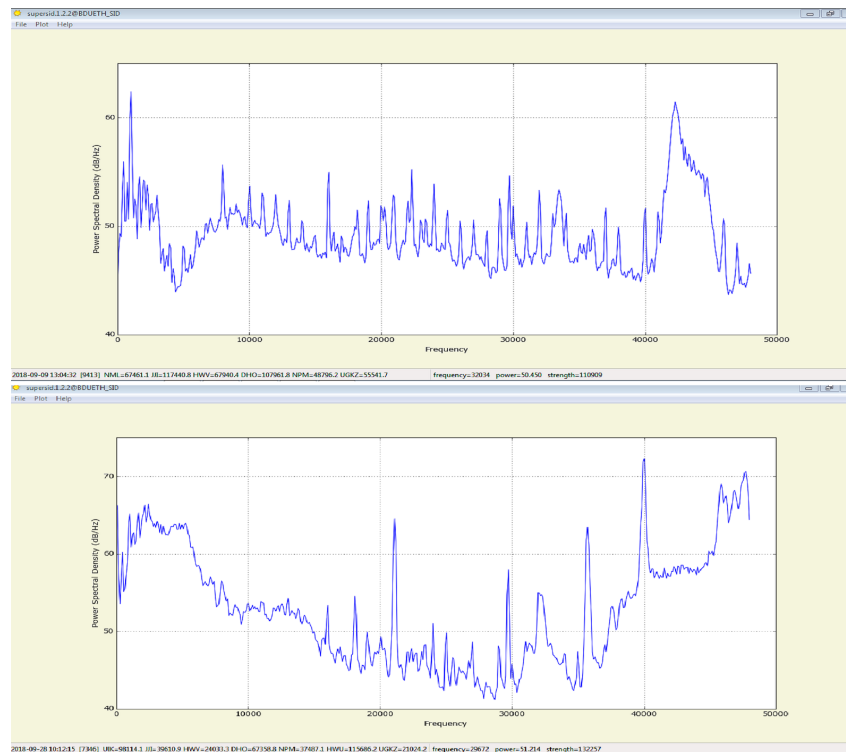


Figure 4.1: Radio Signals Picked up at Two Different Sites, around Bahir Dar University Stadium (Top) and on the roof of Physics Department Laboratory Building (Bottom)

Figure 4.2 shows the VLF signal strength versus time picked by the SuperSID. As seen clearly, the signal strength shows diurnal variations; in the daytime signal strength drops while in the nighttime the signal strength rises. During the daytime, as the transmitted VLF signal passes through the D-region then reflected back at the E-region of the ionosphere, there is an absorption of the signal twice at D-region before it is received at the ground. Therefore, this double absorption at the D-region weakens the signal in the daytime because of increased ionization. But at night, both D and E-regions disappear. As a result we receive a strong radio signal reflected directly from the F-region without absorption in the D or E-regions.

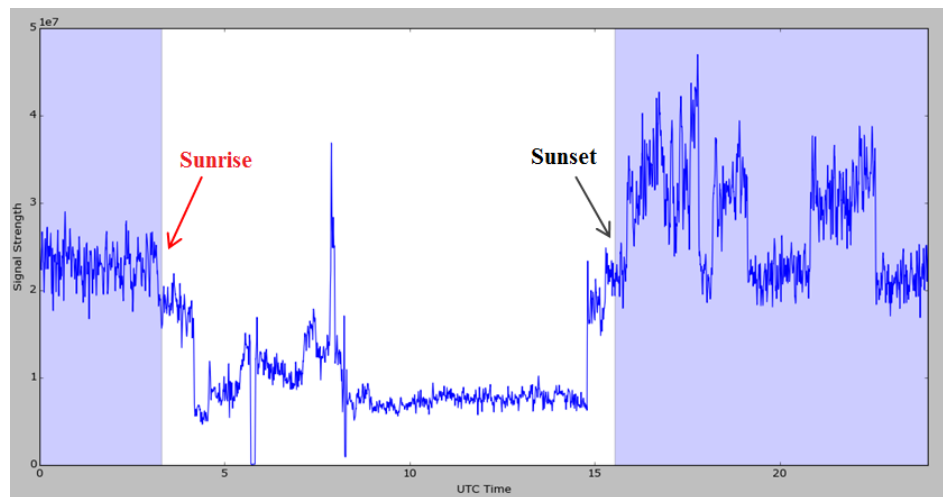


Figure 4.2: Diurnal variation of VLF signal strength collected by SuperSID monitor at Bahir Dar

When we pick up radio transmissions by our SuperSID monitor, if the power cable is unplugged we get spikes like shown in Figure 4.1 which is what one is expected to achieve in using this monitor. But when we plug in the power cable we get the following result in which the radio signal from the stations are masked due to high interference.



Figure 4.3: Interference affecting radio transmissions at receiver site

As it can be seen from Figure 4.3, no clear spikes are observed indicating that the VLF radio transmissions are highly affected by the interference. Since unplugging the power cable gives a better result, noise from the a power source seems the interference source.

4.3 Swarm Data Results and Their Interpretation

On 22-23 June, 2015 geomagnetic storm occurred which was the second strongest storm in the 24th solar cycle next to the 17th March, 2015 geomagnetic storm. On June 22, two CMEs hit the

Earth at 05:45 UT and at 18:30 UT. The first CME resulted small alteration in the Dst index while the second CME which was associated with an M6.6 solar flare resulted a significant change of the Dst index. Recombination of the IMF B_z and magnetic field lines of the Earth resulted a Dst value of -204 nT on June 23, 2015 making the storm the second largest of the 24th solar cycle. The table and figure below show the evolution of the storm depicted by the change in Dst index. The table contains the Dst index values of 22-23 June, 2015 which are interests of our study.

Table 4.1: Dst index in nT measured on the June 22-23, 2015 geomagnetic storm days.

UT	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
22	8	8	9	8	8	11	13	4	6	-2	-5	2	-1	-6	-18	-35	-51	-41	-8	-53	-121	-106	-97	-102
23	-101	-131	-147	-180	-204	-185	-178	-161	-161	-162	-156	-144	-138	-128	-112	-114	-111	-109	-98	-89	-98	-101	-101	-93

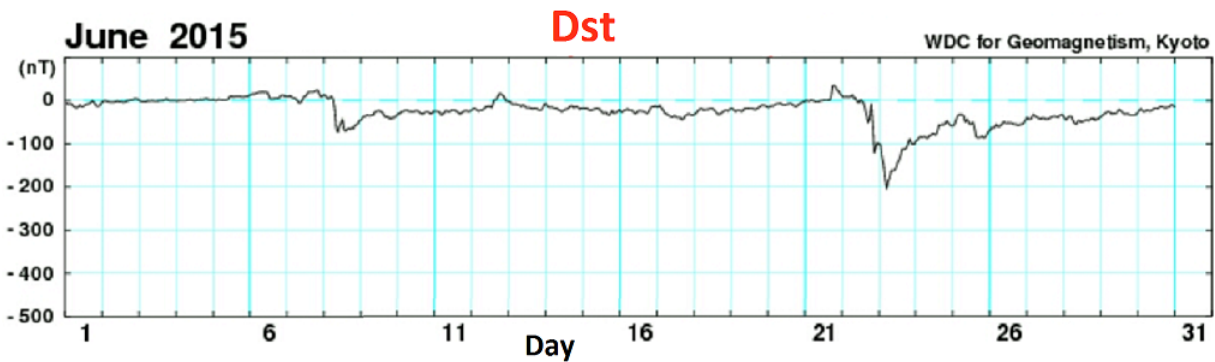


Figure 4.4: Dst Index of June 2015, (Adopted from World Data Center)

The next results and discussions section of this work presents the analysis of Swarm A electron density measurement at orbital height shown in Figure 4.5 on these geomagnetic days.

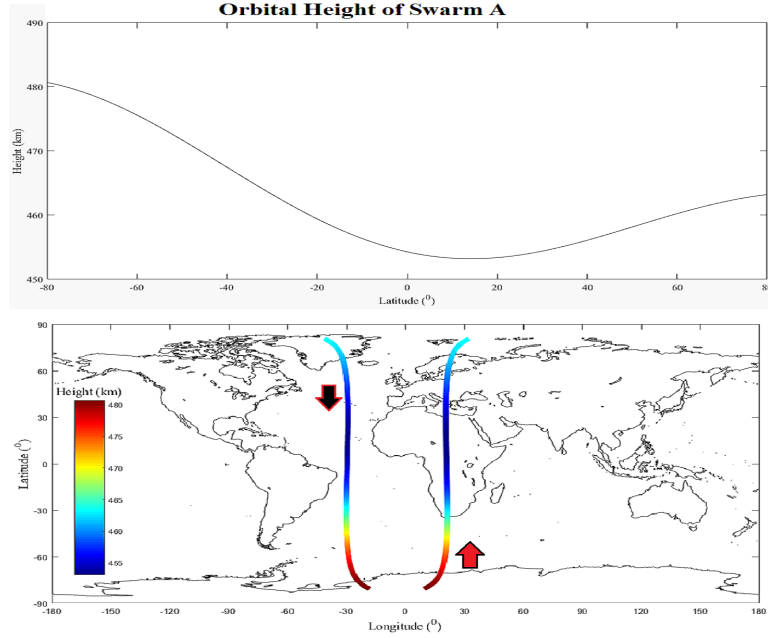


Figure 4.5: Swarm A ascending and descending while orbiting away from and to the equator.

The arrows in the figure show orbiting direction of the satellite. The satellite has taken the dayside and nightside data at about 11 and 23 local times respectively for both days of the storm. But on 22 June, 2015 it was orbiting south to north in the dayside and north to south in the nightside while on 23 June it was in the reverse. We focus on the time interval between arrival time of the first CME and the recovery phase of the storm. Figures 4.6, 5.7 and 4.8 show the dayside electron density of 22 June, 2015 while Figures 4.9, 4.10 and 4.11 show the nightside electron density of 22 June, 2015. We compared both the dayside and nightside storm day electron density with corresponding quiet day data. From 5.01 UT to 10.39 UT, the dayside electron density has shown insignificant disturbance except some observable enhancement at the poles and lower electron density at lower latitudes indicating that the first CME of June 22, 2015 has insignificant impact on the dayside ionosphere.

Dayside Electron Density Data of 22 June, 2015

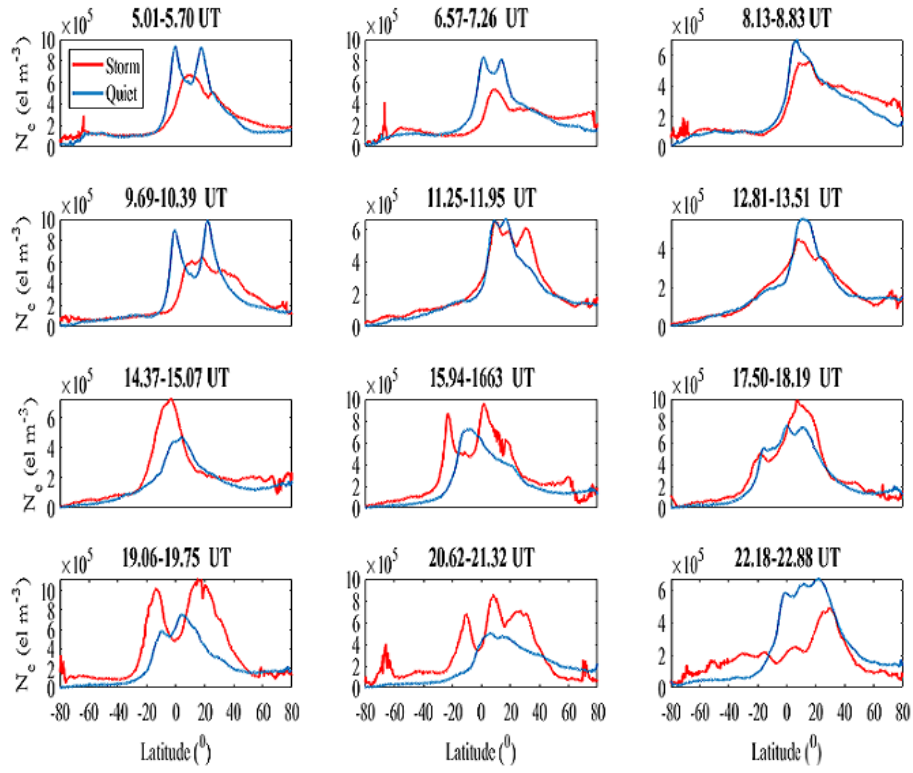


Figure 4.6: Dayside ionospheric Electron Density

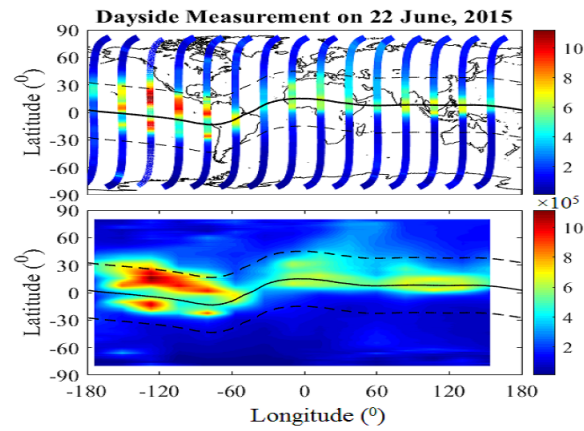


Figure 4.7: Dayside Ionospheric Electron Density

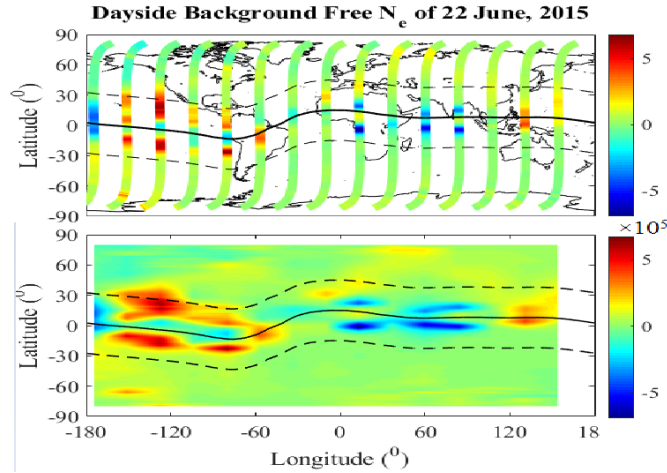


Figure 4.8: Dayside Background Free Electron Density

However, in the nightside in Figure 4.9, starting from 7.35 UT, there is a high ionospheric disturbance with hemispheric asymmetry: high electron density in the northern hemisphere. This disturbance was developed after the first CME hit the Earth. The equatorial ionospheric anomaly (EIA) was strengthened at the nightside and weakened at the dayside. From 14.37 to 21.32 UT in Figure 4.6, at which the storm commenced and developed to the main phase, the electron density increased at low and middle latitudes. The south pole showed a positive storm (resulting electron density enhancement), higher from 20.62-21.32 UT, while the north pole showed both positive and negative storms. From 22.18-22.88 UT, the EIA weakened again with negative and positive storms at the north and south hemispheres respectively. From Figure 4.9, the nightside electron density measurement from 13.55-22.14 UT shows positive southern storm and negative northern storm. In this interval the EIA showed some disturbance in the nightside while the dayside was strengthened.

Nightside Electron Density Data of 22 June, 2015

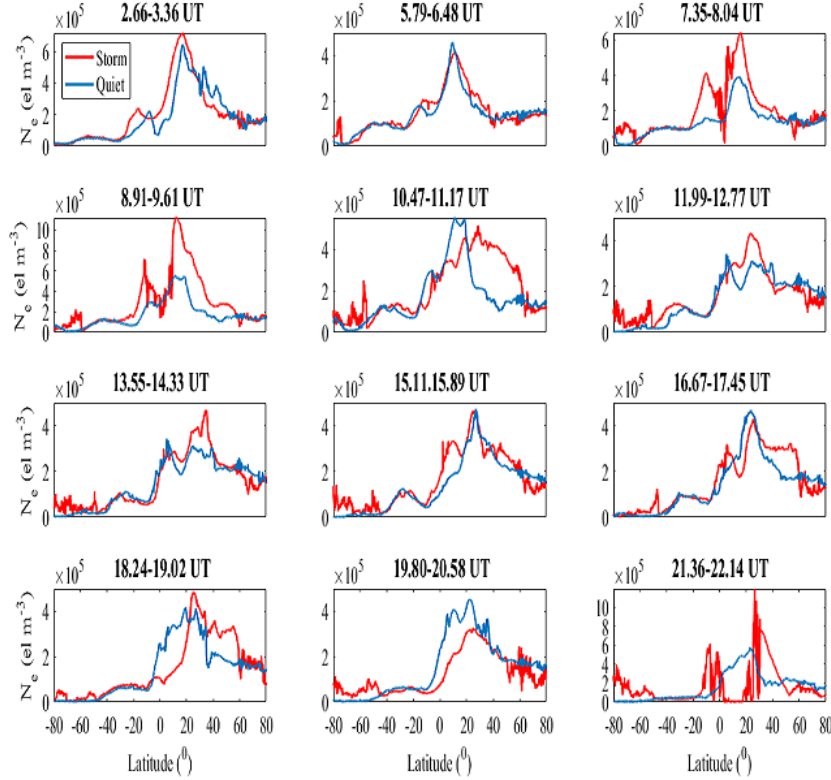


Figure 4.9: Nightside ionospheric response to June 22, 2015 geomagnetic storm

Figures 4.7 and 4.10 show the electron density in situ measurement at different sectors of the globe on the 22 June 2015 geomagnetic storm while 4.8 and 4.11 show the background free electron density. In Figure 4.12, the dayside and nightside responses are compared together in these sectors. The arrows with local time (LT) in the plot are used to indicate the starting point of the orbiting satellite and the direction on that sector. D1 represents the first path of the satellite in the daytime while N1 is for nighttime first path. As one can see from them, the southern hemisphere EIA is highly suppressed in all sectors. The EIA in the Pacific sector is the strongest of all. In addition to that, the daytime and the nighttime EIAs were comparable at this sector. In the day-

time, the African sector had the highly suppressed EIA. These plots show peak electron density

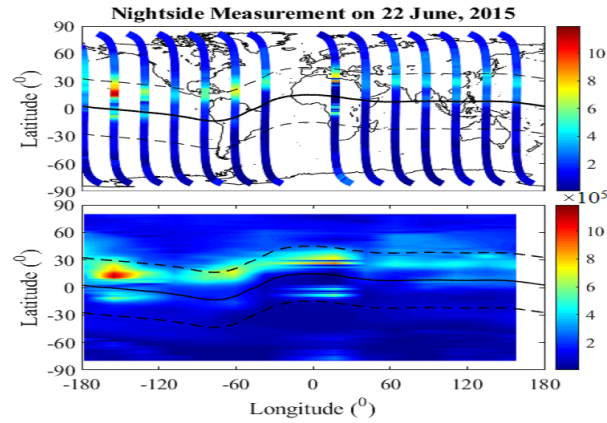


Figure 4.10: Nightside Ionospheric Electron Density

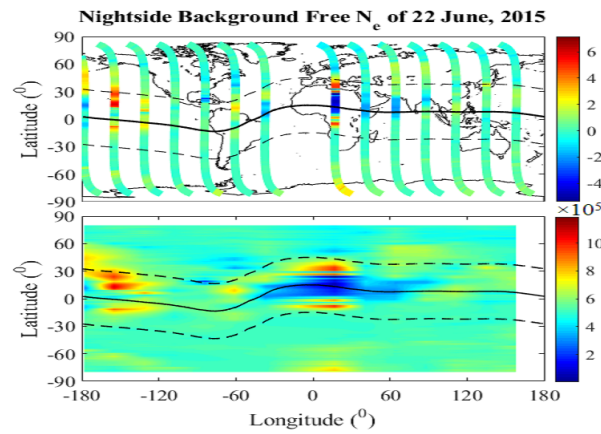


Figure 4.11: Nightside Background Free Electron Density

points as one goes away from the equator to the poles or vice versa. The peak points might be results of TIDs resulting ionization as the disturbances move to or away from the equator. But it seems difficult to track both medium-scale and large-scale TIDs as the life time of them is about 1 hour and 3 hours respectively whereas a Swarm satellite takes about one and half hours for a full revolution. With this configuration, the Swarm satellite has the chance to miss some TIDs or

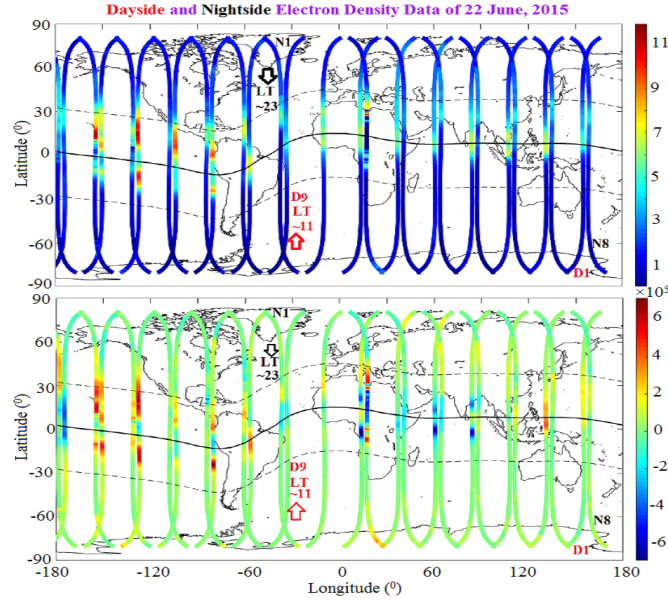


Figure 4.12: Comparison between dayside and nightside electron density measurements (Top), and their respective background free data (Bottom).

to track them and take measurements of the parameters at some points which doesn't enable use to observe clear patterns of poleward or equatorward TIDs and analyse their wave patterns.

One driver of the positive or negative storms is the prompt penetration electric field (PPEF) which is characterized by a southward or northward turning of B_z that produces eastward or westward electric field during the day and westward or eastward electric field during the night respectively (Tesema *et al.*, 2015; Olwendo *et al.*, 2017; Astafyeva *et al.*, 2016). It can have an enhancement or suppression effects depending on the orientation of IMF B_z and the resulting electric field direction. Energy deposition during geomagnetic storms and the resulting disturbance dynamo effect is the other driver in electron density alteration. The disturbance dynamo has an effect of a downward drift on the dayside and an upward drift on the nightside and tends to oppose the

quiet time zonal electric field (Olwendo *et al.*, 2017). Changes in the thermospheric composition ($[O]/[N_2]$ ratio) due to the heating of the thermosphere during geomagnetic disturbances is the other driving factor resulting the positive or negative storms. Increased ratio may favour photo-ionization while a depleted ratio favours recombination, resulting positive and negative storms in their respective order (Liu *et al.*, 2017; Tesema *et al.*, 2015). For detailed investigation and understanding of the exact drivers, one must need multiple instrument data.

Figure 4.13 shows the daytime electron density of 23 June, 2015 geomagnetic storm. In this figure, from 1.30-5.12 UT the electron density was enhanced at low and mid latitudes while it showed oscillation near the poles. After that, which is the beginning of the recovery phase, the

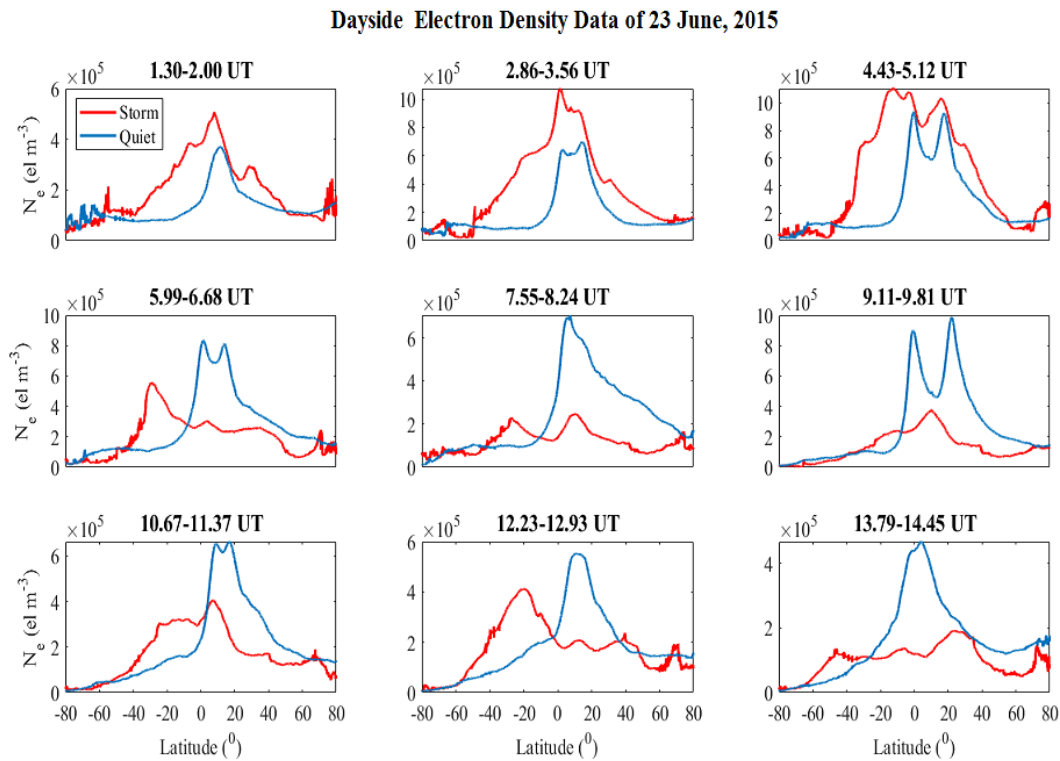


Figure 4.13: Electron density response to June 23, 2015 geomagnetic storm

EIA was highly suppressed. In Figure 4.14, the nighttime observation from 0.52-2.78 UT, the southern auroral oval and the low latitudes showed positive storms while mid and high latitudes of the northern hemisphere showed negative storms with suppressed electron density.

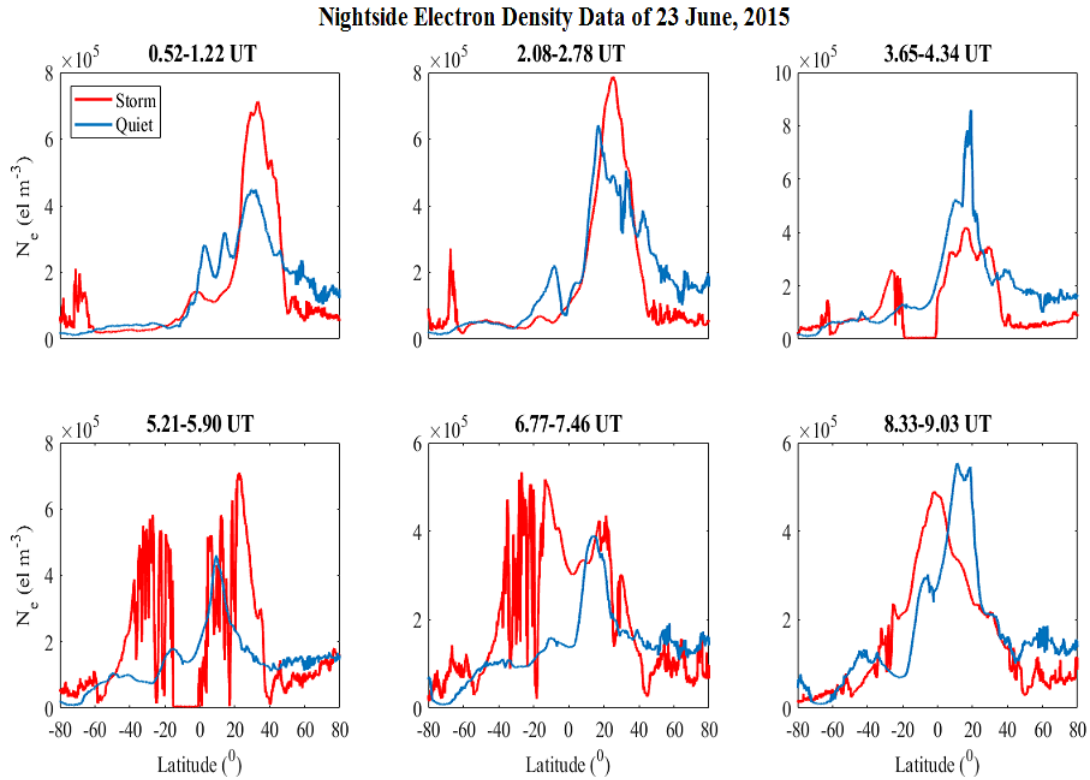


Figure 4.14: Electron density response to June 23, 2015 geomagnetic storm

From 3.65 UT to 4.34 UT, the EIA is strongly weakened while in the next two panels it showed a chaotic oscillation with negative and positive storms in the northern and southern higher latitudes, respectively. The EIA recovered faster at the nighttime than the daytime. PPEF, disturbance dynamo and composition change or combination of them might be the drivers behind.

CHAPTER 5

Conclusions and Recommendations

5.1 Conclusions

In our study we have deployed a SuperSID monitor and investigated the variability of the ionosphere by using radio signal strength data from the SuperSID monitor and electron density data from Swarm satellite. We observed that our SuperSID monitor can pick up a number of radio transmissions from different stations across the globe. Graphs of 24-hours worth data collected using this instrument have showed the day and night variability of the ionosphere via sunrise and sunset signatures of signal strength.

Our investigation of the response of the ionosphere to a geomagnetic storm using Swarm satellite data showed very high variability of the electron density during the event at high latitude region. From 7.35-9.61 UT of 22 June, 2015 the dayside ionosphere showed suppressed EIA while the nightside is strengthened indicating the first CME of the day might have resulted a disturbance dynamo. But in the interval of 13.55-22.14 UT the PPEF seemed to be the dominant driver of the variability. Hemispheric asymmetry of geomagnetic effect was observed , and the June solstice might be the reason behind it. We also observed the nighttime ionosphere recovered sooner.

5.2 Recommendations

The SuperSID monitor that we deployed at Bahir Dar collects data a day. We recommend the noise that interferes the signal when the power cable is plugged in should be reduced and a full daytime data must be recorded. If this problem is resolved, since the SuperSID data processing is easy, Space Physics students can do projects on the daily, weekly and seasonal variations of the ionosphere using data of this monitor. They can observe the variation of sunrise and sunset times, and as a result the day and night time length variations. The students and other interested scientists and researchers can also track the sources of solar flares on the Sun, give predictions of their occurrence and track them using the monitor.

In using the Swarm satellite data for the purpose of investigating the geomagnetic storm effects on the ionosphere, we recommend to use other instrument data such as $[O]/[N_2]$ ratio data to support the Swarm satellite data and conduct detailed analysis. This will help to know the specific disturbance drivers.

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