



RADIOWAVE SCINTILLATION OVER ETHIOPIA USING SCINDA GPS STATIONS

By
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*For those family and friends of mine who have unlimited
potential but can not attend the school.*

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Acronyms

GPS - Global Positioning System

TEC - Total Electron Content

DMSP - Defence Meteorological Sattellite Program

Dst - Disturbed Storm Time

MATLAB - Matrix Laboratory

SCINDA - Scintillation Network Decision Aid

TECU - Total Electron Content Unit

AP - Averaged Planetary A Index

KP - A 3-hourly planetary geomagnetic Index

EA - Elevation Angle

AM - Amplitude Modulation

UTSEC - Universal Time Second

VTEC - Vertical Total Electron Content

SBAS - Satellite Based Augmentation System

SSN - Sun Spot Number

UV - Ultra Violet

VLF - Very Low Frequency

HF - High Frequency

EUV - Extreme Ultra Violet

EMW - Electromagnetic Wave

PRN - Pseudorange Number

TRANSIT - Time Ranging And Sequential

TAI - International Atomic Time
UT - Universal Time
USNO - US Naval Observatory
ECI - Earth Center Inertial
ECEF - Earth Center Earth Fixed
LOS - Line Of Sight
JD - Julian Date
STEC - Slant Total Electron Content
IGS - International GPS Service
IPP - Ionospheric Piercing Paint
RINEX - Receiver Independent Exchange Format (GPS)
EEJ - Equatorial Electrojet
CME - Coronal Mass Ejection
CIR - Co-rotating Interaction Region
IMF - Interplanetary Magnetic Field
SSC - Storm Sudden Commencement
EPBs - Equatorial Plasma Bubbles
WAAS - Wide Area Augmentation System
WDC - World Data Center
LT - Local Time
GCS - Gradual Commencement Storms

Abstract

The low latitude and equatorial ionosphere TEC and S₄ index variability are investigated using observational data. Two GPS stations namely Addis Ababa located at geographic latitude 9°.034 N and longitude 38°.67 E and Bahrdar station geographic latitude 11°.37 N and longitude 37°.10 E are analyzed for the ascending period of solar cycle 24. During the period of observation (January 2008 to December 2014), the variation of scintillations with diurnal, seasonal, magnetic activity, low and high solar activity are presented in this thesis. Due to geographical location influence there were a time shift of peak VTEC and S₄ at both Addis Ababa and Bahir Dar. The occurrence of scintillation is found to be hourly mean maximum in E-season and minimum in D-season. The suppression or enhancement of pre-midnight scintillations during magnetic disturbed and quiet periods is found to be a local time dependent. When the occurrence of geomagnetic storm was observed either to inhibit or to trigger scintillation occurrence. Enhanced scintillation appeared during main and recovery phase of geomagnetic storm. Scintillation was maximum during high sunspot number (2011-2014) and was minimum at low sunspot number (2008-2010). Post-sunset scintillation was found to be maximum in E-season whereas it is minimum in D-season. The elevation angle of PRN satellites have an influence on scintillation occurrence. Pre-reversal enhancement of VTEC is a cause to maximum scintillation ascending during post-sunset.

Keywords: GPS-SCINDA; VTEC, S₄ index, Dst, elevation angle, Geomagnetic storm, low solar activity period, high solar activity period.

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Chapter 1

Introduction

The atmosphere of Earth is a layer of gases surrounding the planet Earth that is retained by Earth's gravity. The atmosphere protects life on Earth by absorbing ultraviolet solar radiation, warming the surface through heat retention (greenhouse effect), and reducing temperature extremes between day and night (the diurnal temperature variation). Ionosphere is a region of partially ionized plasma above the Earth's atmosphere formed due to primarily photo-ionization of the neutral atoms and molecules. The increase in the density of the atmosphere as we go further down to the surface of the Earth and the decrease in the intensity of photons as it bombards the neutral atoms and the availability of different atoms and molecules at different heights from the Earth's surface forms a large scale vertical layer of ionization within the ionosphere. This makes the ionosphere to exist as vertically stratified partially ionized plasma state from at about 60–1000 km from the surface of the Earth[1].

Total Electron Content (TEC) is electrons integrated between two points, along a tube of one meter square crossection and it is given in unite of TECU, and which is defined as $10^{16}/m^2$. TEC is significant in determining the scintillation and group and phase delays of radiowave through a medium. The motion of radiowave over earth atmosphere and in free space is characterized by electromagnetic phenomena such as reflection, refraction, diffraction, polarization and absorption. Scintillation occurs when a radio frequency signal in the form of a plane wave traverses a region of small scale irregularities in

electron density. The irregularities cause small-scale fluctuations in refractive index and subsequent differential diffraction (scattering) of the plane wave producing phase variations along the phase front of the signal. As the signal propagation continues after passing through the region of irregularities, phase and amplitude scintillation develops through interference of multiple scattered signals. Scintillation variability is occurred due to seasonal variation, diurnal, zenith angle, geographical position, different phenomena such as scintillation due to earth's atmosphere, geomagnetic storm and solar cycle.

Scintillation due to geomagnetic storm is characterized by AP, Kp, Dst indices. The equatorial ionospheric parameters, Kp and Dst indices have an indispenseable role in determining and characterizing contribution of different magnetospheric and ionospheric currents to the horizontal component of geomagnetic fields. All the geomagnetic storm indices are used to sense and measure whether the ionosphere electron content is disturbed or not. Depending on the indices it is possible to detect the occurrence of scintillation as well as to determine scintillation scale. Eventhough scintillation has a characterization of like chameleon with solar activities, this work will show scintillation characterization interms of some parameters derived from Global Position System (GPS) for different events at seasonal, diurnal, time scales and, solar and geomagnetic activities. A geomagnetic storm is a temporary disturbance of the Earth's magnetosphere caused by a solar wind shock wave and/or cloud of magnetic field which interacts with the Earth's magnetic field. The increase in the solar wind pressure initially compresses the magnetosphere and the solar wind's magnetic field interacts with the Earth's magnetic field and transfers an increased energy into the magnetosphere. Both interactions cause an increase in movement of plasma through the magnetosphere (driven by increased electric fields inside the magnetosphere) and an increase in electric current in the magnetosphere and ionosphere [2].

In addition, scintillation variation depends on diurnal, seasonal, solar activity, and geomagnetic storm. In this thesis, GPS signal scintillation is assessed over Ethiopia from

two SCINDA GPS stations at Addis Ababa and Bahir Dar based on observations over a period covering the 2008-2014. The thesis is organized as follows. Chapter 2 provides background on atmospheric layers and their distinct features. Chapter 3 presents overview of GPS system and Chapters 4 and 5 discuss TEC variability and ionospheric disturbances respectively. Chapter 6 describes data and methodology used in this work while Chapters 7 and 8 give the discussion of the results and conclusion of the study respectively.

Chapter 2

Layers of earth atmosphere

2.1 Neutral atmospheric layers

The Earth's atmosphere is an envelope of thin gas that surrounds the Earth and extends from the Earth's surface out thousands of kilometres, becoming increasingly thinner (less dense) with distance but always held in place by Earth's gravitational pull. The atmosphere contains the air we breathe and it holds clouds of moisture (water vapor) that become the water we drink. It protects us from meteors and harmful solar radiation and warms the Earth's surface by heat retention. In effect, the atmosphere is an envelope that protects all life on Earth.

The atmosphere is a mixture of gases we call "air". On a dry volume basis, it consists of about 78% nitrogen and 21% oxygen. The remainder of about 1% contains argon, carbon dioxide and very small amounts of other gases. The atmosphere is rarely, if ever, completely dry. Water vapor is almost always present up to about 4% of the total volume. In desert regions, when dry winds are blowing, water vapor in the air will be nearly zero. This climbs in other regions to about 3% on extremely hot and humid days. The upper limit, approaching 4%, is for tropical areas. The atmosphere has a total mass of about metric tons and about 80% of that mass is within about 12 kilometres from the Earth's surface. There is no definite boundary between the atmosphere and outer space. It slowly becomes less dense (i.e., more empty) and fades into the void of outer space^[3].

The atmosphere of the earth, since it is not uniform, can be grouped into different layers

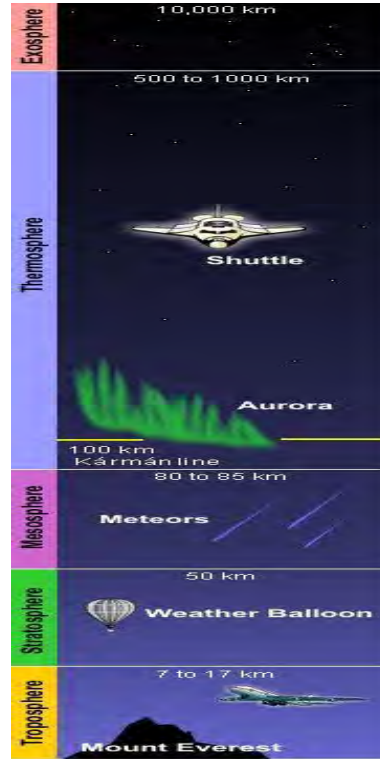


Figure 2.1: Layers of Earth's atmosphere from the lower Troposphere to upper Exosphere (taken from reference [3]).

based on different characters like thermal characteristics (temperature changes), chemical composition, density, and air movement.

Fig. 2.1 shows the earth's atmosphere layers ordered from lowest to the highest layer, as the Troposphere, Stratosphere, Mesosphere, Thermosphere and the Exosphere. There are four boundaries between the primary layers, referred to as Tropopause, Stratopause, Mesopause and the Thermopause.

2.1.1 Troposphere

The troposphere is the lowest layer of the atmosphere which covers a height from the Earth's surface to about 7 kilometres high at the north and south poles and 17 kilometres high at the equator. But its altitudes in different geographical locations depend on time,

season and latitude. As the density of the air in this layer decrease with height, the air temperature in the troposphere also decreases with height. The temperature drops from about 14°C to 15°C at the surface, to about -45°C at the top of the troposphere. All of our weather occurs in the troposphere. The troposphere contains about 80% of the total mass of the atmosphere. In fact, 50% of the total mass of the atmosphere is located in the lowest 5 to 6 kilometres of the troposphere. The cruising (movement) altitude of commercial airliners is usually about 9 to 10 kilometres which is close to the top of the troposphere. In addition to that Troposphere has two parts, planetary boundary layer (the bottom 1 km height) and the free troposphere layer just above 1 km height to the end of the troposphere^[3].

2.1.2 Stratosphere

The stratosphere extends from the tropopause's height of 7 to 17 kilometres to a height of about 50 kilometres and contains about 19% of the atmospheric gases. The stratosphere experiences increasing temperature and solar radiation with height. It contains the ozone layer because the solar radiation is increasingly absorbed by oxygen molecules in the stratosphere, leading to the formation of ozone. Even if the thickness of the stratosphere layer determined by seasonally and geographically in different locations the ozone layer resides in the lower portion of the stratosphere ^[3].

2.1.3 Mesosphere

The mesosphere altitude is from stratopause's height of about 50 kilometres to a height of about 80 to 85 kilometres. The gases continue to become less and less dense with height. As such, the effect of the warming by ultraviolet radiation also becomes less and less, leading to a decrease in temperature with height. On average, temperature decreases to as low as -100°C, at the mesopause. However, the gases in the mesosphere are still

dense enough to slow down meteors hurtling into the atmosphere, where they burn up and leave fiery trails in the night sky. Compared to the other layer it is loosely known for it is at the maximum reach of the aircraft and the minimum reach of the space craft^[4].

2.1.4 Thermosphere

The thermosphere extends from the mesopause's height of 80 to 85 kilometres to a height of between 500 and 1000 kilometres and is referred to as the upper atmosphere. The gases of the thermosphere are increasingly less dense than in the mesosphere. As such, incoming high energy ultraviolet and x-ray radiation from the sun, absorbed by the molecules in this layer, results in the temperature increasing to as high as 2000°C, near the top of this layer. However, despite the high temperature, this layer of the atmosphere would still feel very cold to our skin because of the extremely low density of the air. The total amount of energy from the very few molecules in this layer is not enough to heat our skin. The International Space Station orbits in this layer, between 320 and 380 kilometers from the Earth's surface. The Krmn-line, named after the physicist Theodore von Krmn, is in the thermosphere at an altitude of 100 kilometres above the Earth and is often referred to as the boundary between Earth's atmosphere and outer space ^[5] [6].

2.1.5 Exosphere

Extends from the thermopause's height of 500 to 1000 kilometre up to a height of 10,000 kilometres above the Earth's surface. The exosphere is the outermost layer of the atmosphere and it is in this layer that our man-made satellites orbit the Earth. The density of the exosphere is so low that particles within it (atoms, molecules, or ions) do not collide. As a result, particles in the exosphere can escape altogether from Earth's atmosphere into the void of space^[3].

2.2 The Ionosphere

2.2.1 Introduction

The name ionosphere was proposed by R.A. Watson-Watt in 1926, and came into common use after 1930s, since there are a lot of researches held broadly in the vicinity of ionosphere. The ionosphere is a shell of electrons and electrically charged atoms and molecules that surrounds the Earth, extends from a height of 50 km to more than 1,000 km. It owes its existence primarily to ultraviolet radiation from the Sun.

At heights of above 80 km, in the thermosphere, the atmosphere is so thin that free electrons can exist for short periods of time before they are bonded with a nearby positive ion. These free electrons have negative impact up on radio propagation. This portion of the atmosphere is ionized and contains a plasma which is referred to as the ionosphere. In a plasma, the negative free electrons and the positive ions are attracted to each other by the electrostatic force, but they are too energetic to stay fixed together in an electrically neutral molecule^[7].

Photons from UV, X-ray, shorter wave length of solar radiations have the ability to ionize, using their enough energy production via the photons^[8]. As a result the energy is powerfull to dislodge an electron from the neutral gas atom or molecule. In this process the light electron obtains a high velocity so that the temperature of the created electronic gas is much higher than the one of ions and neutrals and the process is called *photoionisation*, represented as $N_{atom} + h\nu \rightarrow N_{atom}^+ + e^-$. The reverse process to ionization is recombination, in which a free electron is "captured" by a positive ion^[8]. Recombination occurs spontaneously, and results in the emission of a photon carrying away the energy produced upon recombination. As gas density increases at lower altitudes, the recombination process prevails, since the gas molecules and ions are closer together. Acumlation of intense gas density at lower altitudes indicate as the recombination processes may have occured, because the gas molecules and ions are tightly

closer. The balance between these two processes determines the quantity of ionization present^[8].

Generally the amount of ionization in the ionosphere varies greatly with the amount of radiation received from the Sun. Ionization is the process in which electrons, which are negatively charged, are removed from neutral atoms or molecules to leave positively charged ions and free electrons and depends primarily on the Sun and its activity. There are also mechanisms that disturb the ionosphere and decrease the ionization. There are disturbances such as solar flares and the associated release of charged particles into the solar wind which reaches the Earth and interacts with its geomagnetic field.

The ionospheric electron density variation under different conditions has a very vital role to play in understanding the lower as well as the upper atmosphere. The ionosphere is strongly coupled to other regions like the magnetosphere and interplanetary space, whose states affect activities on earth. Signals transmitted for communication and navigational purposes from satellite must definitely pass through the ionosphere, which acts as a perturbing medium on satellite-based navigation systems (for example. density global positioning system)^[9].

2.2.2 Layers of the ionosphere

The ionosphere is an ionized region in the upper atmosphere that, by generally accepted convention, lies between an altitude range of 60-1000 kilometers. Nevertheless the region above 1000 kilometers but below 2000 kilometers, called the protonosphere, is also ionized and may be an important region when considering the totality of ionization effects on radio systems. As a matter of convenience, some specialists have combined the ionosphere and protonosphere into a single region of ionization. For example, the integrated electron density from a ground station to a geosynchronous satellite (referenced to the vertical) is referred to as the total electron content of the ionosphere (i.e. TEC), even though both

ionospheric and protonospheric electrons contribute to the integral^[10].

Due to the availability of different atoms and molecules with changing rates of absorption, the ionosphere at all latitudes has a tendency to stratify as group of regions. However, a series of distinct regions or layers of electron density occurred in the daytime ionosphere at mid- latitudes. These layers are denoted by the letters D, E, F1, and F2 (Fig. 2.2). Each layer is generally characterized by a density maximum at a certain altitude and a density decrease with altitude on both sides of the maximum. The four layers are collectively known as bottomside ionosphere. Peak electron density of the ionosphere occurs usually at the F2 layer and the region above this layer is said to be topside ionosphere. There is a minimum frequency of an electromagnetic wave that can penetrate an ionospheric layer. This frequency is called the critical or plasma penetration frequency of the particular layer and it is denoted by foD, foE, foF1, and foF2 according to the designation of the ionospheric layers.

As shown in Fig. 2.2 which shows the arrangements of ionosphere layers from the bottom to the top of layers.

D layer

The D-region is the lowest region of the ionosphere and which extends about 70 - 90 km. However, to account for the contribution of galactic cosmic rays in the region that lies between 50 - 70 km, its lower boundary is usually placed at 50 km. Ion production in the D region is mainly due to solar x-rays or Lyman ionisation that ionize N_2 and O_2 [11]. Being at a lower altitude, the D region molecules are squeezed closer together by gravity than those in the higher layers, and the free electrons reattach to the molecules easily. This region is important in the characterisation of absorption losses for short wave systems and as a reflecting layer for long wave communication and very low frequency (VLF) waves and navigation systems^[10]. The greatest level of absorption of radio waves is found in this layer. Radio waves at lower frequencies cannot penetrate this layer and are absorbed.

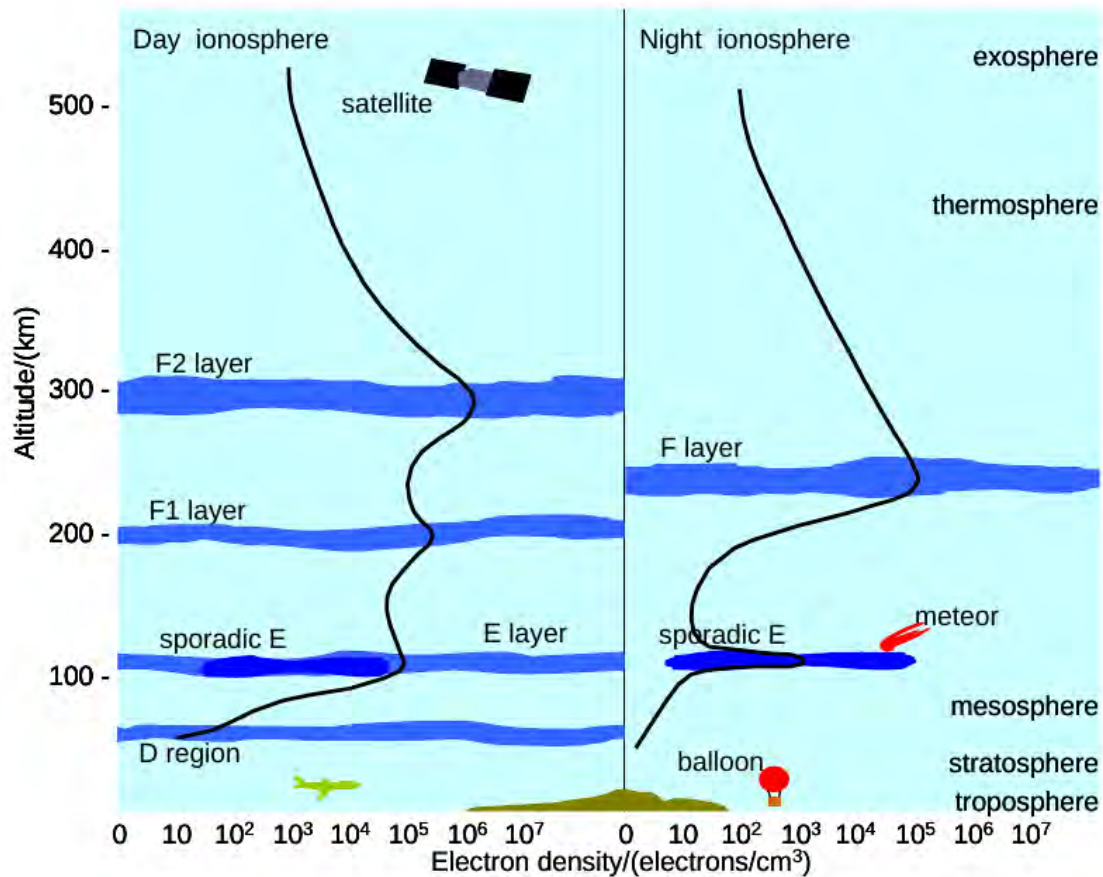


Figure 2.2: Layers of Earth atmosphere and Earth Ionosphere (from the lower to the highest layers order from [http : //www.ips.gov.au](http://www.ips.gov.au)).

The higher frequency signals are able to pass through the D layer. Recombination is high in the D layer, so net ionization is low, and high-frequency (HF) radio waves are significantly damped within the D layer by collisions with electrons (about ten collisions every millisecond). This is the main reason for absorption of HF radio waves, particularly at 10 MHz and below, with progressively smaller absorption as the frequency gets higher. This effect peaks around noon and is reduced at night due to a decrease in the D layer's thickness; only a small part remains due to cosmic rays. A common example of the D layer in action is the disappearance of distant AM broadcast band stations in the daytime^[8].

E layer

The E layer is the middle layer, 90 km to 150 km above the surface of the Earth. Ionization is due to soft X-ray (110 nm) and far ultraviolet (UV) solar radiation ionization of molecular oxygen (O_2). Normally, at oblique incidence, this layer can only reflect radio waves having frequencies lower than about 10 MHz and may contribute a bit to absorption on frequencies above.

However, during intense Sporadic E events, the E_s layer can reflect frequencies up to 50 MHz and higher. The vertical structure of the E layer is primarily determined by the competing effects of ionization and recombination. At night the E layer weakens because the primary source of ionization is no longer present. After sunset an increase in the height of the E layer maximum increases the range to which radio waves can travel by reflection from the layer.

This region is also known as the Kennelly-Heaviside layer or simply the Heaviside layer [8].

The E_s layer (sporadic E-layer) is characterized by small, thin clouds of intense ionization, which can support reflection of radio waves, rarely up to 225 MHz. This propagation occurs most frequently during the summer months when high signal levels may be reached.

F layer

The F layer or region, also known as the Appleton-Barnett layer, extends from about 150 km to more than 500 km above the surface of Earth. It is the most dense layer of the ionosphere, which implies signals penetrating this layer will escape into space. At higher altitudes, the number of oxygen ions decreases and lighter ions such as hydrogen and helium become dominant; this layer is the topside ionosphere. There, extreme ultraviolet (UV, 10100 nm) solar radiation ionizes atomic oxygen. The F layer consists of one layer at night, but during the day, there are F1 and F2 layers. The F2 layer remains by day and night responsible for most skywave propagation of radio waves, facilitating high frequency

(HF, or shortwave) radio communications over long distances.

2.2.3 Production and loss of electrons

Radiation from the Sun causes ionization in the ionosphere. Electrons are produced when solar radiation collides with uncharged atoms and molecules (Fig. 2.3). Since this process requires solar radiation, production of electrons only occurs in the daylight hemisphere of the ionosphere.

Loss of free-electrons in the ionosphere occurs when a free electron combines with a charged ion to form a neutral particle (Fig. 2.4). Loss of electrons occurs continually, both day and night.

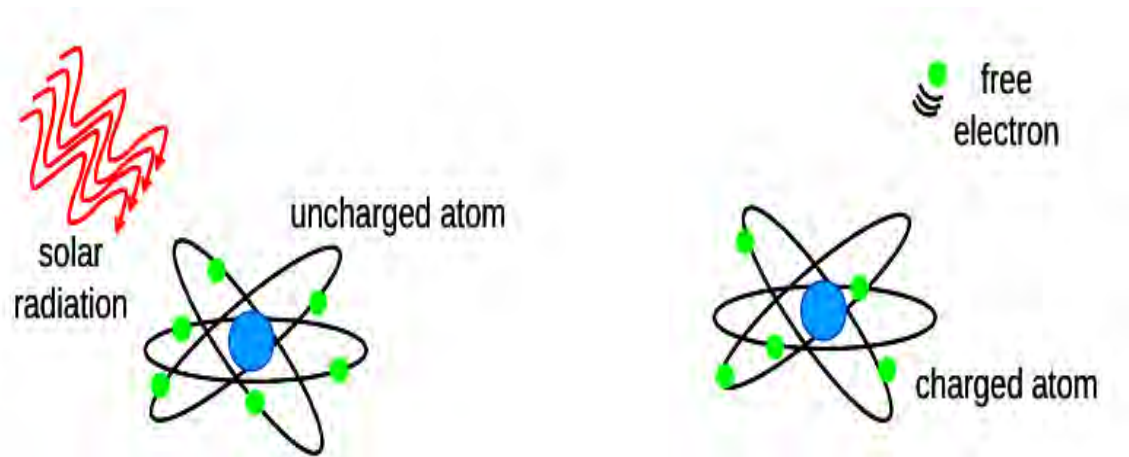


Figure 2.3: Free electron production in the ionosphere (from <http://www.ips.gov.au>).

2.2.4 Ionospheric variations

The ionosphere is not a stable medium that allows to use the same frequency throughout the year, or even over 24 hours. The ionosphere electron density varies with the solar

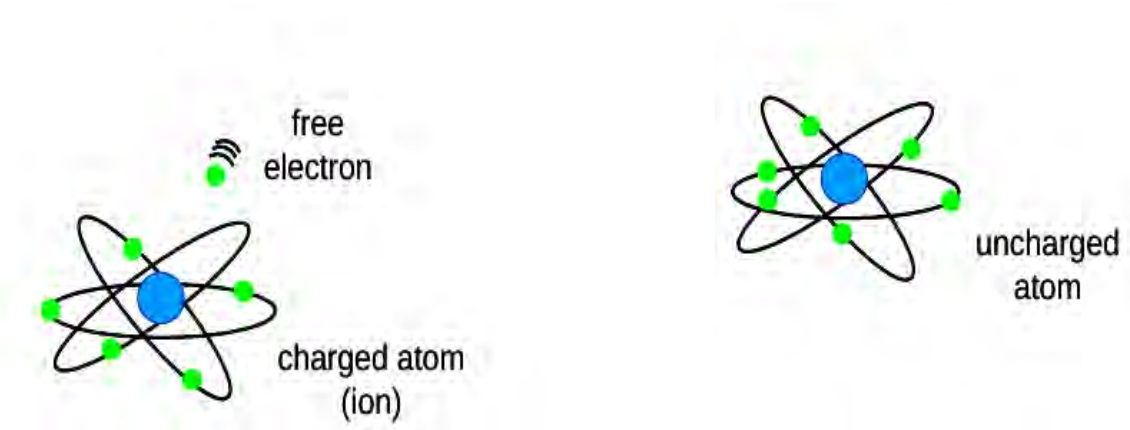


Figure 2.4: Loss of free-electrons in the ionosphere (from <http://www.ips.gov.au>).

cycle, the seasons and during any given day. Generally all the ionospheric variations can be classified easily as regular and irregular ionospheric variations.

Regular ionospheric variation are predictable and occurred with their specific duration such that, diurnal, seasonal, solar activity and latitudinal variations are the most common as regular variation.

Irregular ionospheric variations Irregular ionospheric variations are unpredictable and have a great impact on HF propagation. The common irregular variations include sporadic E, spread F, sudden ionospheric disturbances and ionospheric storms. We can see below the most common general ionospheric variations.

Variations due to the solar cycle

The Sun goes through a periodic rise and fall in activity which affects HF communications; solar cycles vary in length from 9 to 14 years. At solar minimum, only the lower frequencies of the HF band will be supported (reflected) by the ionosphere, while at solar maximum the higher frequencies will successfully propagate. This is because there is more radiation being emitted from the Sun at solar maximum, producing more electrons in the ionosphere which allows the use of higher frequencies.

Diurnal variations

Electron density are normally higher during the day and lower at night due to the variation of radiation from the sun [11]. After dawn, solar radiation causes electrons to be produced in the ionosphere and electron density increase rapidly to a maximum around noon. During the afternoon, electron density begin falling due to electron loss and with darkness the D, E and F1 regions disappear at sun dusk. Communication during the night is conducted only via the F2 (combined F) layer only and attenuation is very low. Through the night, maximum electron density gradually decrease, reaching their minimum just before dawn. All these activities are significantly determined by the solar activities of radiation^[12].

Seasonal variations

The ionosphere exhibits strong seasonal and solar cycle variations because the main source of ionization and energy for the ionosphere is photo-ionization. We can observe the best example from seasonal variation of E region electron density are greater in summer than winter. However, the variation in F region electron density is more complicated. In both hemispheres, F region noon electron density generally peak around the equinoxes (March and September). Around solar minimum the summer noon electron density are, as expected, generally greater than those in winter, but around solar maximum winter electron density tend to be higher than those in summer. In addition, electron density around the equinoxes (March and September) are higher than those in summer or winter for both solar maximum and minimum. The observation of winter electron density often being greater than those in summer is called the seasonal anomaly.

In addition the ionospheric seasonal variation is related to a solar zenith angle change, while its solar cycle variation is related to a change in the solar EUV and X-ray radiation

fluxes. However, the ionospheric variations are not always simple because the ionosphere is closely coupled to the thermosphere, which also undergoes seasonal and solar cycle changes. For example, [13] during the solar cycle 23, investigated that large daytime electron density in winter than in summer called the seasonal anomaly which occurs mainly at mid-latitudes and is more pronounced in the northern hemisphere than in the southern hemisphere.

Variations with Latitude

During the day, with increasing latitude, the solar radiation strikes the atmosphere more obliquely, so the intensity of radiation and the daily production of free electrons decreases with increasing latitude. In the F region this latitude variation persists throughout the night due to the action of upper atmospheric wind currents from day-lit to night-side hemispheres. Deviations from the general low to high latitude decrease are also apparent. Daytime F region electron density peak not at the geomagnetic equator, but 15° to 20° north and south of it. This is called the equatorial anomaly. Also, at night, electron density reach a minimum around 60° latitude north and south of the geomagnetic equator. This is called the mid-latitude trough.

2.2.5 Ionosphere and radio wave propagation

As we have discussed in Section 2.2.2, the distinguishable ionosphere, comprises free electrons and positive ions, generally in equal numbers, in a medium that is electrically neutral. The breakthrough and pioneer of a modern radio was invented by Marconi's well-known experiments in trans Atlantic communication (from Cornwall to Newfoundland) in 1901.

The low-latitude zone, spanning 20° or 30° either side of the magnetic equator, is strongly influenced by electromagnetic forces that arise because the geomagnetic field runs horizontally over the magnetic equator. A strong electric current (an *electrojet*) flows

in the E region, and the F region is subject to electrodynamic lifting and a *fountain effect* that distorts the general form of the ionosphere throughout the low-latitude zone. On the other hand, at high latitudes we find the opposite situation. Here the geomagnetic field runs nearly vertical, and this simple fact of nature leads to the existence of an ionosphere that is considerably more complex than that in either the middle or the low-latitude zones. This happens because the magnetic field-lines connect the high latitudes to the outer part of the magnetosphere which is driven by the solar wind, whereas the ionosphere at middle latitude is connected to the inner magnetosphere, which essentially rotates with the Earth and so is less sensitive to external influence. Thus, the upper atmosphere is said to be a magneto-plasma due to the presence of the geomagnetic field. *The advantages of ionosphere for radio wave propagation* are, low cost of terminal equipment; long distance communication without repeaters; low power requirements; adequate bandwidths for audio communication; and adequate signal strengths over long distances

The disadvantages of ionosphere for radio wave propagation are, variability of propagation conditions; frequent frequency changes; time dispersion due to interference of waves from multiple paths; large and rapid amplitude and phase fluctuations; and interruption by ionospheric storms.

In general the higher frequency radio wave propagations are classified into three (see Fig. 2.5) as follows.

(a) *Ground wave*: near the ground for short distances, up to 100 km over land and 300 km over sea. Attenuation of the wave depends on antenna height, polarisation, frequency, ground types, terrain and/or sea state.

(b) *Direct wave*: this line of sight wave may interact with the earth-reflected wave depending on distance between receiver and transmitter, frequency and polarisation of the signal.

(c) *Sky wave*: this wave is reflected by the ionosphere. Not all HF signals are reflected by the ionosphere, there are upper and lower frequency bounds. If the frequency is too high,

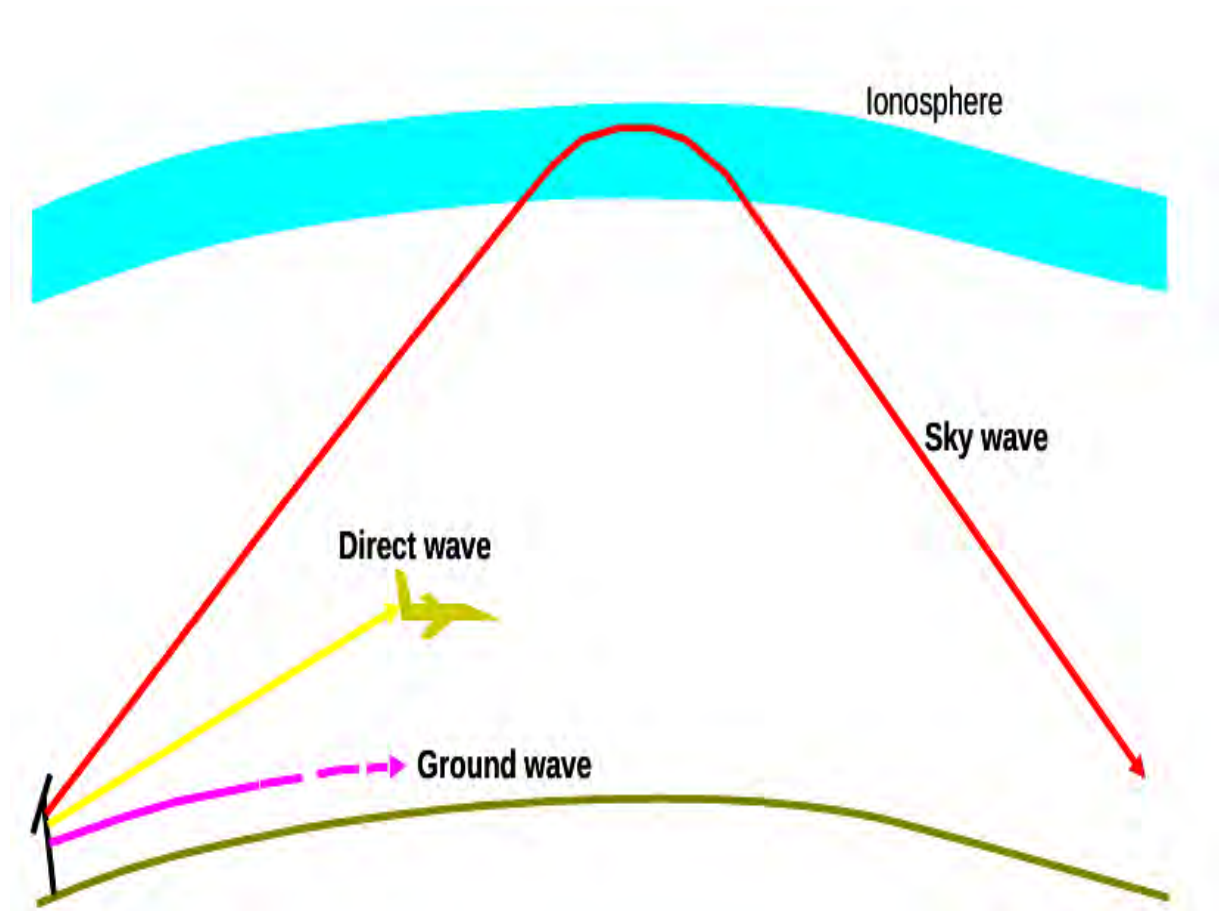


Figure 2.5: Types of higher frequency radio wave propagations (from <http://www.ips.gov.au>).

the radio signal will penetrate through the ionosphere. If the frequency is too low, the strength of the signal will be very low due to absorption in the D region. The range of frequencies between these bounds is in between (usable) frequencies. The range of usable frequencies varies mostly with state of the ionosphere (diurnal, seasonal, solar cycle and geographic location variations).

Chapter 3

The Global Positioning System

3.1 Introduction

The Global Positioning System (GPS) is a satellite-based navigation system for accurate and instantaneous position determination and timing by measuring distance from the satellites. The satellites transmit very low power radio signals allowing anyone with a GPS receiver to determine their location on Earth. The GPS system provides accurate, continuous, world wide, three dimensional position and velocity information to users with appropriate equipment^[14]. According to its organizational structure, the GPS system can be divided into three segments: *the user segment, the space segment and the control segment.*

3.2 GPS segments

1. The Space Segment consists of at least 24 satellites (21 active plus 3 operating spares) is the heart of the system. The satellites are in what is called a high orbit about 20,200 Km above the Earth's surface. Operating at such a high altitude allows the signals to cover a greater area. The satellites are arranged in their orbits so a GPS receiver on earth can receive signal from at least four of them at any given time. Each satellite also transmits its own pseudorandom noise (PRN) code which is used to identify the satellites signal in the receiver, hence the satellites are usually

identified by the prefix PRN followed by the satellite number.

The satellites are powered by solar energy and are built to last about 10 years. If the solar energy fails (due to eclipses, etc.), they have backup batteries on board to keep them running. They also have small rocket boosters to keep them flying in the correct path.

The first GPS satellites were launched into space in 1978. A full constellation of 24 satellites was achieved in 1994, completing the system. Each plane is filled with 4 to 6 satellites spaced to guarantee a minimum visibility of 4 satellite at any time at any location on the globe. To eliminate dispersion and refraction effects due to the Earth's ionosphere, the GPS signals are transmitted on two distinct frequencies L1 band = 1575.42 MHz and L2 band = 1227.6 MHz used by anyone for scientific purposes and a third frequency currently in use by the US military only. L1 contains two pseudorandom (a complex pattern of digital code) signals, the Protected (P) code and the Coarse/Acquisition (C/A) code. Each satellite transmits a unique code, allowing the GPS receiver to identify the signals. Anti-spoofing refers to the scrambling of the P code in order to prevent its unauthorized access. The P code is also called the P (Y) or Y code. The main purpose of these coded signals is to allow for calculating the travel time from the satellite to the GPS receiver on the Earth. This travel time is also called the Time of Arrival. The travel time multiplied by the speed of light equals the satellite range (distance from the satellite to the GPS receiver). The Navigation Message (the information the satellites transmit to a receiver) contains the satellite orbital and clock information and general system status messages and an ionospheric delay model. The satellite signals are timed using highly accurate atomic clocks.

2. The Control Segment as its name implies it controls the GPS satellites by tracking them and then providing them with corrected orbital and clock (time) information. There are five control stations located around the world four unmanned monitoring

stations and one master control station. The four unmanned receiving stations constantly receive data from the satellites and then send that information to the master control station. The master control station corrects the satellite data and, together with two other antenna sites, sends (uplinks) the information to the GPS satellites.

The operational control systems contains a master control station, monitor stations, and ground control stations. The master control station is located at Schriever Air Force Base in Colorado Springs. It collects the tracking data from five monitor stations and calculates the satellite orbit and clock parameters^[15].

3. The User Segment simply consists of GPS receiver.

3.3 GPS observables (measurement)

The signals transmitted by the satellites and received at a GPS user's receiver form the GPS observables, which are manipulated to attain position estimates. The most commonly used GPS Observables are code pseudoranges and carrier phases, including thirdly Doppler measurement of the signal is also hardly used as GPS Observable. The principles of GPS navigation formulations containing different types of GPS measurements are guided by those Observables.

3.3.1 Pseudorange measurement

The pseudorange is the "distance" between the GPS satellite at some transmit time and the receiver at some receive time. As stated before, the ranges from the receiver to the satellites are needed for the position computation. Either the P-code or the C/A-code can be used for measuring the pseudorange. To determine the range in between GPS receiver and the satellite GPS, let us assume for a moment that both the satellite and the receiver clocks, which control the signal generation, are perfectly synchronized with each other. When the PRN code is transmitted from the satellite, the receiver generates an exact

replica of that code^[16]. Some time later, equivalent to the signal travel time in space, the transmitted code will be picked up by the receiver. By comparing the transmitted code and its replica, the receiver can compute the signal travel time. Multiplying the travel time by the speed of light ($3 \times 10^8 m/s$) gives the range between the satellite and the receiver (Distance = Velocity x Travel Time). Unfortunately, the assumption that the receiver and satellite clocks are synchronized is not exactly true. In fact, the measured range is contaminated, along with other errors and biases, by the synchronization error between the satellite and receiver clocks. For this reason, this quantity is referred to as the pseudorange, not the range^[16]. GPS was designed so that the range determined by the civilian C/A-code would be less precise than that of military P-code. This is based on the fact that the resolution of the C/A-code, 300m, is 10 times lower than the P-code. Surprisingly, due to the improvements in the receiver technology, the obtained accuracy was almost the same from both codes^[16].

3.3.2 Carrier phase measurement

The Carrier phase is a measure of received phase signal of a satellite relative to the receiver generated carrier phase at the reception duration. The received signal phase is tracked by shifting the receiver generated phase. A full carrier phase is called *cycle*, with the frequencies f_1 and f_2 the wavelength of one cycle is 19cm and 24cm respectively. Range measurement based on carrier phase would simply be the sum of the total number of full carrier cycles plus fractional cycles at the receiver and the satellite, multiplied by the carrier wavelength. The ranges determined with the carrier phases are far more accurate than those obtained with the code pseudoranges. This is due to the fact that the wavelength (or resolution) of the carrier phase, 19 cm in the case of f_1 frequency, is much smaller than those of the codes^[16].

3.3.3 Doppler measurement

Some of the first solution models proposed for GPS were to use the Doppler observable as with the TRANSIT (Time Ranging and Sequential) system. This system used the integrated Doppler shifts (i.e., phase differences) which were scaled to delta ranges^[17].

3.4 GPS time system

Time plays a very important role in positioning with GPS, the GPS signal is controlled by accurate timing devices, the atomic satellite clocks. As we have seen in section 3.3.1, measuring the ranges (distances) from the receiver to the satellites is based on both the receiver and the satellite clocks. GPS is also a timing system, that is, it can be used for time synchronization. A number of time systems are used worldwide for various purposes [16]. The most common GPS time systems are, *Universal Time (UT)* and the *GPS Time* are frequently used by GPS users. UT is an atomic time scale based on the International Atomic Time (TAI). TAI is a uniform time scale, which is computed based on independent time scales generated by atomic clocks located at various timing laboratories throughout the world. In surveying and navigation, however, a time system with relation to the rotation of the Earth, not the atomic time, is desired. As a result the time system of GPS is related to the atomic time system and which referenced to coordinated universal time (UT) as maintained by the US Naval Observatory (USNO). Nominally the GPS time has a constant offset of 19 seconds with TAI, the international atomic time,

$$TAI = GPStime + 19.000s. \quad (3.4.1)$$

Starting at the GPS standard epoch, the system time of GPS is counted in terms of GPS weeks and seconds within the current week. For the calculation of the GPS week, we use the relation

$$WEEK = INT[(JD2444244.5)/7] \quad (3.4.2)$$

where JD indicates the Julian Date and INT is an integer operator.

3.5 GPS errors and biases

GPS signals propagate along their fixed paths from the satellites to the receiving stations by crossing via different mediums as a result the GPS may be exposed to different errors. In general, GPS accuracy performance depends on the quality of the pseudorange and carrier phase measurements as well as the broadcast navigation data. In addition, the fidelity of the underlying physical model that relates these parameters is relevant. For better understanding we will see these errors, classified as those originating from the satellites, those originating from the receiver, and those that are due to signal propagation (atmospheric refraction).

3.5.1 Ephemeris errors

In astronomy and celestial navigation, an ephemeris (plural: ephemerides; from Latin ephemeris, "diary", from Greek ephemeris, "diary, calendar") gives the positions of naturally occurring astronomical objects as well as artificial satellites in the sky at a given time or times. Global Positioning System (GPS) navigation satellites transmit electronic ephemeris data consisting of health and exact location data. A GPS receiver can use the transmissions from multiple such satellites to calculate its own location using triangulation. In order to determine your position, a GPS receiver must know two things. First, it must receive very accurate timing information from multiple GPS satellites. Second, the position of those satellites should precisely be determined. Timing information is broadcast continuously, so that several measurements can be taken each second. **Almanac data:** tells the GPS receiver roughly where all the GPS satellites are. Each satellite transmits the full almanac every 12.5 minutes so, a GPS receiver which knows nothing at all can determine the rough location of the satellites in less than 15 minutes.

Ephemeris data: Once it's determined their rough location, a GPS receiver can listen for ephemeris data. Each satellite broadcasts this data, which tells the receiver its precise orbit, every 30 seconds. Because it is very precise, ephemeris data is only valid for 30

minutes.

The orbit quality is considered to be one of the primary accuracy limiting factors in the GPS measurements. Ephemeris errors occur when the GPS message does not transmit the correct orbital parameters. The ephemeris information used to calculate the satellite position is based on the observations from the monitor stations of the space segment. An ephemeris error for a particular satellite is identical to all GPS users worldwide^[18]. However, as different users see the same satellite at different view angles, the effect of the ephemeris error on the range measurement, and consequently on the computed position, is different. This means that combining (differencing) the measurements of two receivers simultaneously tracking a particular satellite cannot totally remove the ephemeris error. Users of short separations, however, will have an almost identical range error due to the ephemeris error, which can essentially be removed through differencing the observations.

3.5.2 Relativistic error

Since the reference frame (relatively) at rest is located at the center of the earth and an accelerated reference frame is connected with each GPS satellites, consequently theory of special and general relativity must be taken into account. Relativistic effects are relevant for *the satellite orbit, the satellite signal propagation, and both the satellite and receiver clock*^[17]. Both Einsteins general and special theories of relativity are factors in the pseudorange and carrier-phase measurement process^[14]. For special relativity relativistic corrections arises any time the signal source (GPS satellites) or the signal receiver (GPS receiver) is moving with respect to the chosen isotropic light speed frame, which in the GPS system is the Earth-centered inertial (ECI) frame. For general relativity relativistic corrections arises any time the signal source and signal receiver are located at different gravitational potentials. General relativity arises as signals sources and receivers are located at different gravitational potentials. The satellite clock is affected by both special and general relativity. To compensate these effects the fundamental frequency (f_0) of

GPS system is emitted 10.23 MHz. All clocks on the GPS satellites and GPS receivers operate based on this frequency to calculate the difference between the setting frequency f' of satellite clock and the fundamental (f_0), called the offset in the satellite clock frequency^[14] [19]. The consequence of Earth rotation during the time of signal conveying, occurred relativistic error is, known as the *Sagnac effect*^[14], when computations for the satellite positions are made in an Earth-centered Earth-fixed (ECEF) coordinate system. Corrections for the Sagnac effect are often referred to as Earth rotation corrections.

3.5.3 Atmospheric effects

Unlike the ionosphere, atmosphere is non dispersive for GPS signals, which mean that atmospheric effects are independent of the GPS signals. The effects of GPS signals affecting atmosphere is known as *atmospheric delay or tropospheric delay*. The atmospheric delay in the zenith direction can reach up to 2m. All the occurrence of atmospheric delay are grouped as *mixture with out water vapor* which is termed as dry or "hydrostatic" delay and *due to water vapor* termed as "wet delay", which may be zero if there is no water vapor along the path of the signal.

The propagation speed of a wave in a medium can be expressed in terms of the index of refraction for the medium. The index of refraction is defined as the ratio of the waves propagation speed in free space to that in the medium by the formula

$$n = \frac{c}{v} \quad (3.5.1)$$

where c is the speed of light equal to $3 \times 10^8 m/s$. The medium is dispersive if the propagation speed (or, equivalently the index of refraction) is as a function of the waves frequency. In a dispersive medium, the propagation velocity V_p of the signals carrier phase differs from the velocity V_g associated with the waves carrying the signal information. To clarify the concepts of group and phase velocities, consider two components, S_1 and S_2 , of an electromagnetic wave with frequencies f_1 and f_2 and phase velocities v_1 and v_2 ,

traveling in the x-direction. The sum S of these signals is

$$S = S_1 + S_2 = \sin\omega_1(t - \frac{x}{v_1}) + \sin\omega_2(t - \frac{x}{v_2}) \quad (3.5.2)$$

Using the trigonometric identity,

$$\sin\alpha + \sin\beta = 2\cos\frac{1}{2}(\alpha - \beta).\sin\frac{1}{2}(\alpha + \beta) \quad (3.5.3)$$

$$S = 2\cos[\frac{1}{2}(\omega_1 - \omega_2)t - \frac{1}{2}(\frac{\omega_1}{v_1} - \frac{\omega_2}{v_2})x] \times \sin[\frac{1}{2}(\omega_1 + \omega_2)t - \frac{1}{2}(\frac{\omega_1}{v_1} + \frac{\omega_2}{v_2})x] \quad (3.5.4)$$

$$= 2\cos\frac{1}{2}(\omega_1 - \omega_2)[t - \frac{\frac{x}{\frac{1}{2}(\omega_1 - \omega_2)}}{\frac{1}{2}(\frac{\omega_1}{v_1} - \frac{\omega_2}{v_2})}] \times \sin[\frac{1}{2}(\omega_1 + \omega_2)t - \frac{1}{2}(\frac{\omega_1}{v_1} + \frac{\omega_2}{v_2})x] \quad (3.5.5)$$

The cosine part is a wave group (the modulation imposed on the sinusoid that part of the wave which carries the information) that moves with velocity

$$v_g = \frac{\frac{1}{2}(\omega_1 - \omega_2)}{\frac{1}{2}(\frac{\omega_1}{v_1} - \frac{\omega_2}{v_2})} = \frac{2\pi(f_1 - f_2)}{2\pi(\frac{f_1}{v_1} - \frac{f_2}{v_2})} = \frac{f_1 - f_2}{\frac{1}{v_1} - \frac{1}{v_2}} = \frac{(\frac{v_1}{\lambda_1} - \frac{v_2}{\lambda_2})}{(\frac{1}{\lambda_1} - \frac{1}{\lambda_2})} \quad (3.5.6)$$

therefore the equation reduces to,

$$v_g = \frac{(\frac{v_1}{\lambda_1} - \frac{v_2}{\lambda_2} + \frac{v_1}{\lambda_2} - \frac{v_2}{\lambda_1})}{(\frac{1}{\lambda_1} - \frac{1}{\lambda_2})} = v_1 - \lambda_1 \frac{v_2 - v_1}{\lambda_2 - \lambda_1} \quad (3.5.7)$$

where λ_1 and λ_2 are the corresponding signal wavelengths. For signals with narrow bandwidths relative to the carrier frequency, such as the GPS signals, we can replace $v_2 - v_1$ by the differential dv , $\lambda_2 - \lambda_1$ by the differential $d\lambda$;

$$v_g = v_p - \lambda \frac{dv_p}{d\lambda} \quad (3.5.8)$$

Eq. (3.5.8) shows that the relation and differences between group velocity and phase velocity depends on the wavelength and the rate of phase velocity change.

The corresponding refractive index is

$$n_g = n_p + f \frac{dn_p}{df} \quad (3.5.9)$$

where the indices of refraction are as follows

$$n_p = \frac{C}{v_p}, \quad n_g = \frac{C}{v_g} \quad (3.5.10)$$

f denotes the signal frequency. In a nondispersive medium, wave propagation is independent of frequency, and the signal phase and signal information propagate at the same speed with $v_g = v_p$ similarly $n_g = n_p$. All these are about atmospheric effects on GPS measurements are dictated from^[14].

3.5.4 Ionospheric effects

Unlike the atmosphere, an ionosphere is a dispersive medium, which means it bends the GPS radio signal and changes its speed as it passes through the various ionospheric layers to reach a GPS receiver. Bending the GPS signal path causes a negligible range error, particularly if the satellite elevation angle is greater than 5° . Due to the ultraviolet and X-ray radiations coming from the sun interact with the gas molecules and atoms as a result a portion of the ionosphere becomes ionize and then some free electrons are released to the ionosphere layer consequently. GPS satellites are also affected for its signal broadcasts. Ionospheric delay is the change in the propagation speed that causes a significant range error, and therefore should be accounted for. The ionospheric delay is proportional to the number of free electrons along the GPS signal path, called the *total electron content (TEC)*. However, TEC depends on a number of factors: (1) the time of day (electron density level reaches a daily maximum in early afternoon and a minimum around midnight at local time); (2) the time of year (electron density levels are higher in winter than in summer); (3) the 11-year solar cycle (electron density levels reach a maximum value approximately every 11 years, which corresponds to a peak in the solar flare activities known as the solar cycle peak in 2001 we are currently around the peak of solar cycle number 24); and (4) the geographic location (electron density levels are minimum in midlatitude regions and highly irregular in polar, auroral, and equatorial regions). Since this thesis is on TEC and amplitude radiowave scintillation, we focus on TEC GPS measurements. When the ionosphere is a dispersive medium, it causes a delay that is frequency dependent. The lower the frequency, the greater the delay; that is, the L2

ionospheric delay is greater than that of L1. Generally, ionospheric delay is of the order of 5m to 15m, but can reach over 150m under extreme solar activities, at midday, and near the horizon. As we discussed in the previous section 2.2.5 the electron density level varies corresponding with time and location. It is, however highly correlated over relatively short distances, and therefore differencing the GPS observations between users of short separation can remove the major part of the ionospheric delay. Taking advantage of the ionospheres dispersive nature, the ionospheric delay can be determined with a high degree of accuracy by combining the P-code pseudorange measurements on both L1 and L2. Unfortunately the P-code is accessible by authorized users only. With the addition of a second C/A-code on L2 as part of the modernization program, this limitation will be removed. The L1 and L2 carrier-phase measurements may be combined in a similar fashion to determine the variation in the ionospheric delay, not the absolute value. Users with dual frequency receivers can combine the L1 and L2 carrier-phase measurements to generate the ionosphere-free linear combination to remove the ionospheric delay. In general it is difficult to model the ionospheric effect on GPS signals due to complicated physical interactions among geomagnetic field and solar activities. GPS system is designed with several working frequencies, so that ionospheric effect can be measured or corrected using the fact that the ionosphere is dispersive.

The disadvantages of the ionosphere-free linear combination, however, are: (1) it has a relatively higher observation noise, and (2) it does not preserve the integer nature of the ambiguity parameters. As such, the ionosphere-free linear combination is not recommended for short baselines. Single-frequency users cannot take advantage of the dispersive nature of the ionosphere. They can, however, use one of the empirical ionospheric models to correct up to 60% of the delay. The most widely used model is the Klobuchar model, whose coefficients are transmitted as part of the navigation message. Another solution for users with single frequency GPS receivers is to use corrections from regional net works. Such corrections can be received in real time through communication

links. Now here below are the mathematical nomenclature of ionospheric effects from Eq. (3.5.10) it is possible to approximate the following equations using Taylor and Macularin serieses:

$$n_p = 1 + \frac{c_2}{f^2} + \frac{c_3}{f^3} + \frac{c_4}{f^4} + \dots \quad (3.5.11)$$

Where the coefficients c_2 , c_3 , and c_4 are frequency as a function of the number of electrons (i.e., electron density = n_e) along the satellite to user signal propagation path. We can also determine n_g by differentiating Eq. (3.5.11) with respect to "f=frequency" then substituting it in to Eq. (3.5.9), we obtain:

$$n_g = 1 - \frac{c_2}{f^2} - \frac{c_3}{f^3} - \frac{c_4}{f^4} - \dots \quad (3.5.12)$$

By negleting the higher orders, we get the following approximations

$$n_p = 1 + \frac{c_2}{f^2}, \quad n_g = 1 - \frac{c_2}{f^2} \quad (3.5.13)$$

Substituting the plasma frequency $c_2 = n_e^2 / \varepsilon_0 m_e$, m_e is mass of the electron. c_2 is estimated as $c_2 = -40.3n_e Hz^2$, therefore the refractive index becomes

$$n_p = 1 - \frac{40.3n_e}{f^2}, \quad n_g = 1 + \frac{40.3n_e}{f^2} \quad (3.5.14)$$

and the phase velocity and group velocity are also modified as follows by inserting Eq. (3.5.14) into Eq. (3.5.10)

$$v_p = \frac{c}{1 - \frac{40.3n_e}{f^2}}, \quad v_g = \frac{c}{1 + \frac{40.3n_e}{f^2}} \quad (3.5.15)$$

Perhaps, we can observe from Eq. (3.5.15) that the phase velocity exceeds the group velocity. The amount of retardation of the group velocity is equal to the advance of the carrier phase with respect to free-space propagation. In the case of GPS, this translates to the signal information (e.g., PRN code and navigation data) being delayed and the carrier phase experiencing an advance, a phenomenon referred to as *ionospheric divergence*. Importantly, the magnitude of the error on the pseudorange measurement and the error

on the carrier-phase measurement (both in meters) are equal only if the sign is different. The reduction in the carrier-phase measurement value due to the presence of free electrons in the ionosphere can be intuitively explained as being due to the fact that the distance from crest to crest in the electric field of the signal is lengthened for the portion of the signal path contained within the ionosphere. The measured range is

$$S = \int_{SV}^{User} n ds \quad (3.5.16)$$

The geometric range is also

$$l = \int_{SV}^{User} dl \quad (3.5.17)$$

The path length difference due to ionospheric refraction is

$$\Delta S_{iono,p} = \int_{SV}^{User} n ds - \int_{SV}^{User} dl \quad (3.5.18)$$

The delay attributed to the phase refractive index is

$$\Delta S_{iono,p} = \int_{SV}^{User} \left(1 - \frac{40.3n_e}{f^2}\right) ds - \int_{SV}^{User} dl \quad (3.5.19)$$

Similarly, the delay induced by the group refractive index is

$$\Delta S_{iono,g} = \int_{SV}^{User} \left(1 + \frac{40.3n_e}{f^2}\right) ds - \int_{SV}^{User} dl \quad (3.5.20)$$

Since the delay will be small compared to the satellite-to-user distance, we simplify Eq. (3.5.19) and Eq. (3.5.20) by integrating the first term along the LOS path. Thus, ds changes to dl , and we now have

$$\Delta S_{iono,p} = \frac{-40.3}{f^2} \int_{SV}^{User} n_e dl, \quad \Delta S_{iono,g} = \frac{40.3}{f^2} \int_{SV}^{User} n_e dl \quad (3.5.21)$$

The electron density along the path length is referred to as the *total electron count* (TECU) and is defined as

$$TEC = \int_{SV}^{User} n_e dl \quad (3.5.22)$$

The TEC is a function of time of day, user location, satellite elevation angle, season, ionizing flux, magnetic activity, sunspot cycle, and scintillation. It nominally ranges

between 10^{16} and 10^{19} , with the two extremes occurring around midnight and mid-afternoon, respectively. We can now rewrite Eq. (3.5.21) in terms of the TEC[20]:

$$\Delta S_{iono,p} = -\frac{40.3TEC}{f^2}, \quad \Delta S_{iono,g} = \frac{40.3TEC}{f^2} \quad (3.5.23)$$

Since the TEC is generally referenced to the vertical direction through the ionosphere, the previous expressions reflect the path delay along the vertical direction with the satellite at an elevation angle of 90° (i.e., zenith angle). For other elevation angles, we multiply Eq. (3.5.23) by an obliquity factor[20]. The obliquity factor, also referred to as a mapping function, accounts for the increased path length that the signal will travel within the ionosphere. Since the ionospheric delay is determined by frequency, which is helpful to reduce by ranging measurements with a dual-frequency receiver.

3.5.5 Multipath effect

Multipath (see Fig. 3.1) is the phenomenon whereby a GPS signal arrives at a receivers antenna via more than one different paths, due to different obstacling of the signals coming from (example, mountains, trees, weather conditions). Multipath propagation affects both pseudorange and carrier phase measurements.

Multipath is a very localized effect, which depends on the local environment surrounding the antenna. Multipath errors vary significantly in magnitude depending on the environment within which the receiver is located, satellite elevation angle, receiver signal processing, antenna gain pattern, and signal characteristics. Errors which arise as a result of multipath cannot be reduced by the technique of Differential GPS or DGPS, since they depend on the local reflection geometry near each receiver antenna. The multipath effects can be minimized by choosing the site of observation with minimum obstructions and reflecting nearby surfaces.

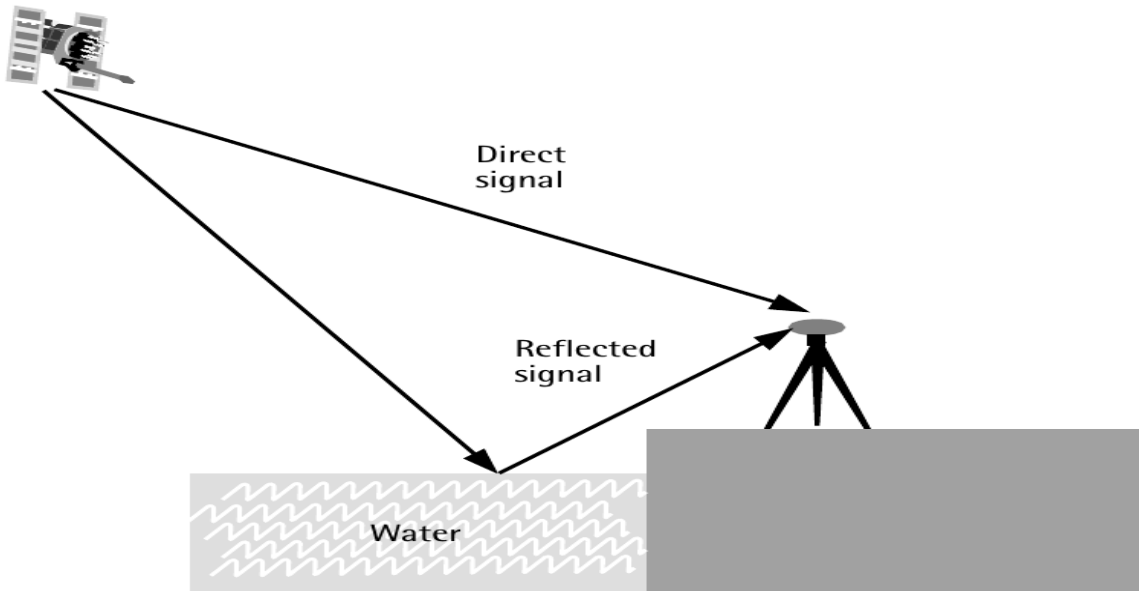


Figure 3.1: Multipath Effect (taken from reference [8]).

3.5.6 Instrument biases

These error sources are introduced by the different travel time of the GPS signal on the two separate frequencies through the hardware of satellite and receiver. The relative delay on the satellite is commonly named as transmitter group delay and the delay caused by the receiver is called receiver inter-frequency bias.

3.5.7 Receiver clock errors

GPS receivers are equipped with inexpensive quartz crystal oscillators with low accuracy. The offset between receiver clock time and GPS time is the receiver clock error which affect all satellite receiver ranges measured at a particular epoch. The performance of the satellite clocks is monitored by the ground control system. The GPS satellite clocks, although highly accurate, are not perfect. This means that the satellite clock error is about 8.64 to 17.28 ns per day. The corresponding range error is 2.59m to 5.18m, which can be easily calculated by multiplying the clock error by the speed of light ($3 \times 10^8 \text{m/s}$).

GPS receivers, in contrast, use inexpensive crystal clocks, which are much less accurate than the satellite clocks. That's why, the receiver clock error is much larger than that of the GPS satellite clock. The breakthrough solution of this type of error to remove is, employing through differencing between the satellites or it can be tolerate as an additional unknown parameter in the estimation process.

Chapter 4

Ionospheric Total Electron Content (TEC)

4.1 Introduction

In the recent years, the measurements of total electron content (TEC) have initiated great interest due to highly increasing demands in the GPS-based technologies, navigation applications, in trans-ionospheric communications with space-borne vehicles, such as satellites, aircrafts and surface transportations. The TEC measurements are obligatory in order to make an appropriate range delay corrections which is happen by the ionosphere, both during quiet (periods with out ionospheric disturbance) and disturbed periods (space weather events). TEC is one of the most important quantitative parameters of the Earth's ionosphere and plasmasphere.

4.1.1 TEC measurements

TEC has been measured experimentally since the 1960s using a variety of different techniques. While there have been relatively few purpose-built satellites for such observations, it has often been possible to make use of radio signals from satellites launched for another primary purpose. Some early measurements involved determination of the polarisation rotation of VHF transmissions from the first generation of geosynchronous communications satellites. Later it became possible to exploit the signals from the various GPS systems. A vast body of data and information about total electron content has been collected

over the years from numerous locations giving almost worldwide coverage. In addition, products have been developed in the form of regional and global models yielding total electron content, while more recently maps are now routinely available. Another recent advance has been the application of tomographic techniques to invert electron content measurements to obtain images of ionospheric electron density.

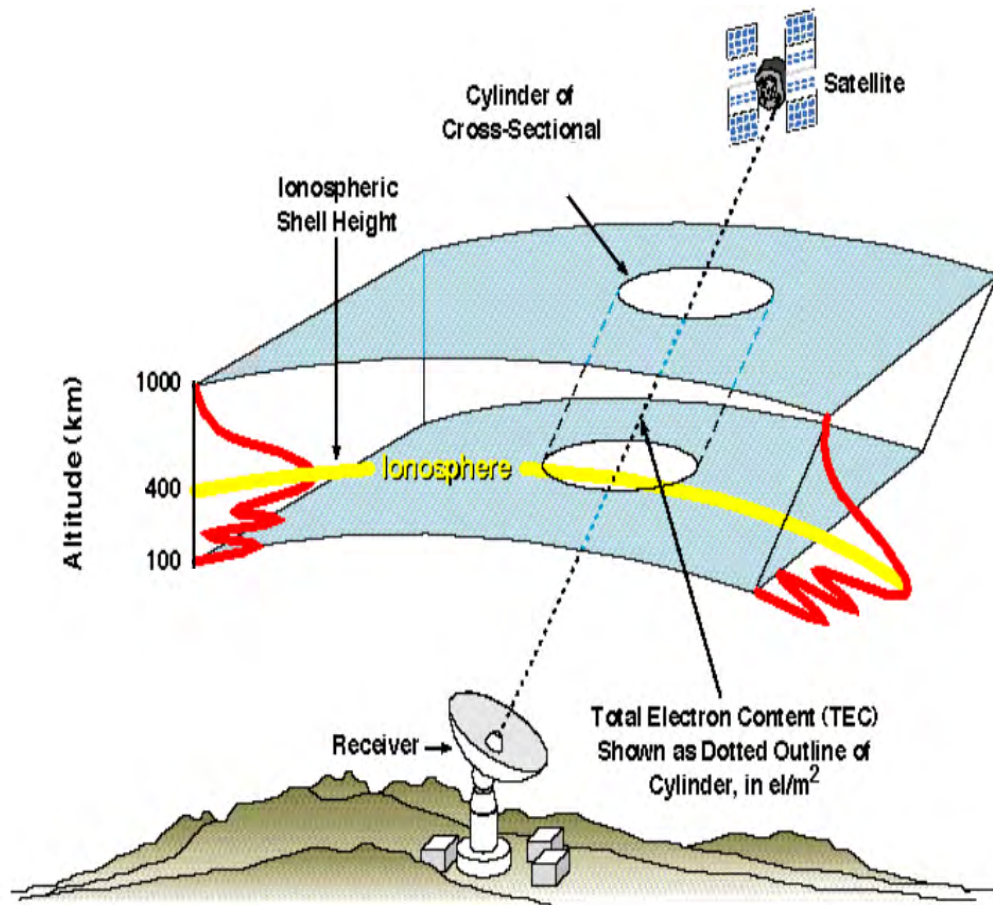


Figure 4.1: A total electron content through 1 m^2 area cylindrical tube (from [http : //docslide.us/documents/atmosphere – and – waves – a – mcgourty – rideout – tutorial.html](http://docslide.us/documents/atmosphere_and_waves_a_mcgourty_rideout_tutorial.html) or The Atmosphere-MIT Haystack Observatory ppt).

Most measurements and applications of total electron content are concerned with arbitrary slant ray paths between a satellite and a ground station. However, for comparative purposes it is necessary to define the observations in a more standard way. In consequence, the convention was adopted at an early stage to apply a simple geometrical construction,

usually based on an assumed thin-shell ionosphere at a fixed height, to rotate the actual slant measurement to obtain an equivalent vertical total electron content. Most estimates of total electron content measured are based on this equivalent vertical parameter[21].

The Slant Total Electron Content (STEC) is the measure of the total number of free electrons in a column of the unit cross section along the path of the electromagnetic wave between the satellite and the receiver. The total number of free electrons is proportional to the ionospheric differential delay between L1 (1575.42 MHz) and L2 (1227.60 MHz) signals[22]. In addition the slant TEC (STEC) can be obtained from Eq. (3.5.20) and can be determined the STEC from

$$STEC = \int N_e ds \quad (4.1.1)$$

For comparison purposes among sets of STEC data the vertical electron content VTEC is formed as

$$VTEC = \frac{STEC}{F} \quad (4.1.2)$$

where F is obliquity factor or mapping function calculated as

$$F = \frac{1}{\cos(z^i)} \quad (4.1.3)$$

where z^i is zenith angle between the signal path and horizontal plane in the mean altitude (h). Using IPP, Earth radius and h, the zenith angle (z^i) of the Satellite for an observer of receiver is

$$z^i = \arcsin\left(\frac{R_E}{R_E + h}\right) \times \sin(z) \quad (4.1.4)$$

where R_E is radius of the earth, IPP is ionospheric piercing point of the single path to satellite, z^i is zenith angle between the signal path and horizontal plane. In addition to that we can also calculate GPS-TEC as follows, using combination of RINEX file, ephemeris from IGS navigation:

$$Z = [\sin^{-1}(0.94792 \times \cos(elevation))] \quad (4.1.5)$$

$$VTEC = \frac{STEC - (b_R + b_S)}{S(E)} \quad (4.1.6)$$

$$S(E) = \frac{1}{\cos(Z)} = (1 - (\frac{R_E * \cos(E)}{R_E + h_S})^2)^{-1/2} \quad (4.1.7)$$

where b_S refers satellite bias, b_R refers receiver bias, $S(E)$, refers projection angle, E refers elevation, R_E refers radius of the earth and, h_S refers height of ionospher.

4.2 TEC variability

Observations of the ionosphere at smaller time scales reveal continual variations. A number of physical processes have been suggested as being the cause of these spatial and temporal variations^[23] ^[24]. Aurora and solar events cause variations in time scales of seconds to hours. Atmospheric temperature and pressure changes are evident in the ionospheric variations since the ionosphere is coupled with the lower atmosphere. Variations of the magnetic, (during magnetic storms and sub-storms) and electric fields induce variations in the parameters that characterize the state of the ionosphere^[24].

4.2.1 Diurnal variation

The ionospheric electron density exhibits regular variations, with a peak during the day to a minimum during the night. This variation of TEC is occured with different amount of total electron content between day and night even, there is also hourly TEC variation in 12 hours of night and 12 hours of day^[25]. This is because of the amount of total electron content is typically depend on the radiation from the sun. The temporal variabilities are however latitude and altitude dependent. In general, the diurnal variation of TEC shows a short lived pre-dawn minimum, a steady early morning increase, followed by an afternoon maximum and gradual fall after sunset. The observations of diurnal variation in TEC show that the time at which TEC reaches the diurnal peak vary from day to day and month to month. In general, the diurnal peak in TEC is found during 1200-1400 hrs LT^[22],^[26]. Large variations in TEC are observed in daytime, while nighttime variations are found

to be almost constant. As generally, the net diurnal change in the quiet day low latitude ionosphere mostly depend on the photo-ionization production and recombination losses associated with the local solar radiation and the field-aligned diffusion of the transported electrons from the equator.

4.2.2 Seasonal variation

The seasonal variations in TEC is due to the tilt and rotation of the earth around the Sun; the relative position of the Sun moves from one hemisphere to the other with seasonal variation of solar zenith angle and intensity of radiation at any geographical location. Eventhough the whole year is categorized into four seasons usually, i.e., December solstice (November, December and January), March equinox (February, March, and April), June solstice (May, June, and July) and September equinox (August, September, and October), but here we have grouped into three seasons based on space oriented seasons . Which are, December solstice; D-season (November, December, January, February); equinox or E-season (March, April, September, October) and June solstice or J-Season (May, June, July, August). Scientists also classify equinox into March-equinox and September-equinox. Similarly solstice seasons also grouped into December-solstice and June-solstice. Having these informations, during equinoctial seasons, the sub-solar point remains around the equator resulting in high photo-ionizations. But during December (sub-solar point is in the northern hemisphere), and June solstice (when the sub-solar point is in the southern hemisphere), low ionization occurs above the equatorial region. The amplitude of the diurnal TEC maximum is higher in the equinoxes and lower in the solstices, thus exhibiting the semiannual variation. Further, the relatively higher TEC during the winter than the summer solstice could be due to the winter anomaly (or seasonal anomaly) which is more prevalent at the northern hemisphere, and during the high solar activity periods. Although the winter anomaly at the mid-latitude to high-latitude regions mostly depend on changes in the O/N_2 ratio, the scenario at the low latitude region is the outcome of

the additional equatorial electrodynamics over the region. TEC is highly enhanced during the equinox seasons where as, TEC is lower during solstice seasons[26]. The equatorial anomaly crests are highly enhanced near local mid-day during winter, however post-noon and later afternoon for both equinox and summer seasons respectively. In addition, the bi-developed crests are move equatorward with significantly during winter condition, but which moves to some extent to poleward during summer and autumn seasons[27].

4.2.3 Latitudinal variation

The intensity of radiation and production of free electrons decrease with increasing latitude. Near the geomagnetic equator, the geomagnetic field is horizontal, and the electric field is eastward during the day and westward at night due to dynamic effect by atmospheric motion. This allows the region to be prone to the equatorial electro-dynamic phenomena. The E-region electric field is mapped into F-layer through out the $(\vec{E} \times \vec{B})$ drift of plasma which then at higher altitudes, because the Hall and Pederson conductivities decrease and the presence of gravity the plasma diffuses along the slope of magnetic field lines at approximately $\pm 15^\circ$ geomagnetic latitudes forming crests on both the hemispheres and forming equatorial ionospheric anomaly region. The larger the plasma drift strength at the equator, the higher is the EEJ and the greater is the strength of anomaly with the crest at farther latitude from the equator. Hence, the TEC is believed to be increased gradually towards the anomaly crest regions, beyond which the value further decreases to attain lower value at mid-latitude regions.

Chapter 5

Ionospheric disturbances

5.1 Introduction

The ionospheric disturbance may stay for a few hours to a few days and tend to occur during times of geophysical disturbance resulting from increases in solar activity communicated via the solar wind[28]. It can result from solar disturbances that occur on the Sun, and from geomagnetic disturbances, which are triggered in more complex ways by events initiating from the Sun. These events affect the outermost geomagnetic field lines and compress the geomagnetic field causing geomagnetic disturbances[29]. Thus, the set of ionospheric disturbances is associated either directly or indirectly with events on the Sun[30].

5.1.1 Ionospheric storms

Solar flares or coronal mass ejection (CME) result in the enhanced flux of intense energetic particles emitted by the Sun. These enhanced flux releases often generate enormous variations in the particle and electromagnetic radiation incident upon Earth and such variations can result in disturbances of the quiet time magnetosphere and ionosphere. The disturbances of the ionosphere are identified as ionospheric storms, which have a tendency to produce large disturbances in ionospheric density distribution and total electron content. These storms symbolize an extreme form of space weather, which has social and technological impacts on space borne and ground based technological

systems[30]. There are also three phases of ionospheric disturbances (F-layer, according to Hargreaves); *initial phase or positive phase* which lasts for a few hours, the electron density and the electron content are greater than normal; *main or negative phase* when these quantities are reduced below normal values; and *recovery phase* is the last event of the whole storm. The most likely cause of the main phase is abnormal heating at high latitude, which also alters the pattern of circulation of the thermospheric wind. The heating reduces the ratio $[O]/[N_2]$ at given height in the F region, and the molecularly enriched air is then convected down to the middle latitudes by the changed air circulation[28].

5.1.2 Geomagnetic storms

A geomagnetic storm is a temporary disturbance of the Earth's magnetosphere caused by transfer of energy and momentum from a solar wind shock wave and/or cloud of magnetic field which interacts with the Earth's magnetic field[31]. The increase in the solar wind pressure initially compresses the magnetosphere and the solar wind's magnetic field interacts with the Earth's magnetic field and transfers an increased energy into the magnetosphere[2]. Both interactions cause an increase in movement of plasma through the magnetosphere (driven by increased electric fields inside the magnetosphere) and an increase in electric current in the magnetosphere and ionosphere.

During the main phase of a geomagnetic storm, electric current in the magnetosphere creates a magnetic force which pushes out the boundary between the magnetosphere and the solar wind. The disturbance in the interplanetary medium which drives the geomagnetic storm may be due to a solar coronal mass ejection (CME) or a high speed stream (co-rotating interaction region or CIR) of the solar wind originating from a region of weak magnetic field on the Sun's surface. The frequency of geomagnetic storms increases and decreases with the sunspot cycle. CME driven storms are more common during the maximum of the solar cycle and CIR driven storms are more common during the minimum of the solar cycle. Like the ionospheric storm, this classical magnetic storm

consists of three phases: (a) an increase of magnetic field lasting a few hours only, called the initial phase; (b) a large decrease in the H component building up to a maximum in about a day, the main phase; and (c) a slow recovery to normal over the next few days, the recovery phase.

5.1.3 Magnetic indices

In the absence of direct measures of activity in the ionosphere and magnetosphere, the geomagnetic indices are used as proxies for the solar and geomagnetic disturbance levels. In turn, the majority of computational space weather simulations (empirical and physics based models) use geomagnetic indices to indicate the solar and geomagnetic disturbance levels. These magnetic indices were primarily intended to define discrepancies in the geomagnetic field, triggered by irregular current systems between the magnetosphere and ionosphere. Commonly these indices are derived from parameters which are monitored continuously with ground-based equipment. The space weather scientific community mostly makes use of the Kp, Ap and Dst indices, which are briefly described as follows [28], [30].

The Kp (planetary Kennziffer) is based on the range of variation within 3-h periods of the UT day observed in the records from about a dozen selected magnetic observatories. After local weighting, and averaging, the Kp value for each 3-h of the day is obtained on a scale from 0 (for very quiet) to 9 (for very disturbed). The scale is quasi logarithmic, and the integer values are sub-divided into thirds by use of the symbols + and -: thus, 2, 2+, 3-, 3, 3+, etc. The Kp index is usually used to measure the strength of a geomagnetic storm and can be scaled as follows:

- 0-3: quiet magnetic condition;
- 3-6: moderate magnetic storm and
- 6-9: disturbed magnetic condition.

The Ap index (or daily equivalent planetary amplitude) is a 3 hour index that is equivalent (linear) in range and is derived from the Kp index values. Some applications in space

weather require a daily index, and the K sum is not suitable because of its quasi-logarithmic nature. The daily Ap index can be defined as the earliest occurring maximum 24 hour value, computed as an 8 point running average of consecutive 3 hour Ap indices through a geomagnetic storm event. It is distinctively coupled with the storm event. Since Ap is derived from Kp, it is also a mid-latitude geomagnetic index.

The Disturbed Storm Time (Dst) index is an index that measures the intensity of a geomagnetic storm and the development of the ring current . Dst is expressed in nano Teslas and is derived from the average value of the horizontal component of the Earth's magnetic field measured hourly at a network of four near equatorial geomagnetic observatories. These observatories make this measurement possible due to averaging the horizontal component of the geomagnetic field from equatorial and mid latitude magnetograms from the universal set-up of magnetometers. The Dst index value tends to a negative value since the Earth's field weakens (particularly during solar storms), due to increase in the strength of the ring current[32], which moves around the Earth in an easterly to westerly direction in the equatorial plane. The Dst index is a particularly useful index of storm strength since the strength of surface magnetic field at low latitudes is inversely proportional to the energy content of the ring current, which increases during geomagnetic storms[33]. Ring currents result from differential gradient and curvature drift of electrons and protons in the nearby Earth region, and its strength is coupled to the solar wind conditions. This is due to the presence of an electric field arising from magnetospheric convection, which in turn results from the interconnection between the southward IMF and the geomagnetic fields. Once the IMF moves in a northward direction and ring current recovers, the Dst index value gradually increases back to its quiet time level[33]. Because the physics of the coupling between the ring current and ground-based magnetometers is well understood, the Dst index is a good proxy for mid-latitude geomagnetic activity. The initial phase is characterized by Dst (or its one-minute

component SYM-H) increasing by 20 to 50 nT in tens of minutes. The initial phase is also referred to as a storm sudden commencement (SSC). However, not all geomagnetic storms have an initial phase and not all sudden increases in Dst or SYM-H are followed by a geomagnetic storm. The main phase of a geomagnetic storm is defined by Dst decreasing to less than -50 nT. The selection of -50 nT to define a storm is somewhat arbitrary. The minimum value during a storm will be between -50 and approximately -600 nT. The duration of the main phase is typically between 2 and 8 hours. The recovery phase is the period when Dst changes from its minimum value to its quiet time value. The period of the recovery phase may be as short as 8 hours or as long as 7 days. The geomagnetic storms can be classified according to different Dst index levels as: weak level when $-50\text{nT} \leq \text{Dst} \leq -30\text{nT}$; moderate level when $-100\text{nT} \leq \text{Dst} \leq -50\text{nT}$ and intense level when $\text{Dst} < -100\text{nT}$ [31].

5.1.4 Ionospheric scintillations

What is ionospheric scintillation?

The Ionospheric scintillation is a rapid random fluctuation of radio-frequency signal phase and/or amplitude, regulated by signal passes through the ionosphere, when a plane wave traverses a region of small scale irregularities in electron density. Due to a small fluctuation in refractive index of a medium of the signals, the ionospheric irregularities leads to skew (bend) the signals path, which depends on the differential of electrons; consequently the scintillation is occurred[34]. In case of signal frequency beyond 3 GHz only tropospheric scintillation due to atmospheric turbulence along the propagation can occur, and which results degradation of signal[35]. Such effects arise from radio frequency propagation through regions where small-scale irregularities in electron density exist. These regions can range in size from a few meters to a few kilometers, and they cause both refraction and diffraction of EM waves propagating through the ionosphere.

Scintillation is caused by small-scale fluctuations in the refractive index of the

ionospheric medium which in turn are the result of inhomogeneities. Inhomogeneities in the ionospheric medium are produced by a wide range of phenomena (eg plasma bubbles), and those responsible for scintillation occur predominantly in the F-layer of the ionosphere at altitudes between 200 and 1000km. In addition to that the scintillation may occur in different phenomena, scintillation occurred with time variation, location variation, geomagnetic variation. Since the equatorial ionosphere is highly dynamical, unpredictable and is characterized by the existence of intense equatorial plasma bubble associated irregularities; during low and moderate solar activity the occurrence pattern of equatorial ionospheric irregularities varies with local time and that only the occurrence probability of irregularities based on plasma density perturbations is consistent with the occurrence of scintillation at all local times[36]. Equatorial plasma bubbles (EPBs) has a significant role as source of ionospheric radio wave scintillation that can cause disruptions and outages of important radio-related informations such as GPS Systems and ground-to-satellite radio communication[37].

Perhaps amplitude scintillation directly influences the signal to noise ratio (C/No) of signals in a GPS receiver, as well as the noise levels in code and phase during their measurement process. Amplitude scintillation can be sufficiently severe so that the received GPS signal intensity from a given satellite drops below the receivers tracking threshold, causing loss of lock on that satellite, and hence the need to reacquire the GPS signal(s). One of best example of this problem is low accuracy of navigation communication, data loss and cycle slip when the amplitude scintillation occur[34]. The phase scintillation has a great impact on phase oriented systems in general.

Measuring ionospheric scintillation

Ionospheric scintillations are categorized into amplitude scintillations and phase scintillations. Amplitude scintillations are caused by irregularities with scale sizes of tens of meters to hundreds of meters more precisely at and below the Fresnel radius, which is approximately

360 m for GPS L1 frequency (1575.42 MHz) and a phase screen altitude of 350 km[38].

This thesis is based on amplitude GPS scintillation measurement from two SCINDA GPS stations, at Addis Ababa and Bahir Dar. Addis Ababa is found at 9°03'N, 38°67'E and Bahri Dar is located at 11°37'N, 37°10'E. The amplitude scintillation is determined using the standard deviation of a signal power, this is expressed by scintillation index(S_4). The S_4 index is the ratio of the standard deviation of the signal power to the mean signal power computed over a period of time, which is written as [38]:

$$S_4 = \sqrt{\frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}} \quad (5.1.1)$$

where I is the signal intensity[38].

Where $\langle \rangle$ represents the average values over a 60-second interval, which can be approximated by the time averages of I . S_4 is a unitless parameter with a theoretical maximum value of S_4 is 1.0, which records within 1 minute time intervals by GPS. This time period is nominally 60s but could be arbitrarily larger or smaller, the time period must be long compared to the Fresnel length divided by the irregularity drift speed[39].

The scintillation parameters are extracted using a dual frequency GPS receiver (1575.42 MHz and 1227.60 MHz) NovAtel GSV 4004B and which records 7 years long. The three regims of scintillation intesity level are Weak $0.2 < S_4 \leq 0.4$; moderate $0.4 < S_4 \leq 0.6$ and strong $0.6 < S_4 \leq 1$ [40]. For $S_4 = 0.0$, this indicates no modulation and for $S_4 = 1.0$, this indicates 100 percent modulation[41].

GPS Antenna should be installed with high altitude, with minimal obstructions from buildings, other interferences equipments, like antennas, power lines, mountains and trees. Antenna cable length greater than 30m is not recomendad at all[42]. The GPS acecessories are as indicated in Fig. 5.1. The different components shown by numbers are: (1), NovAtel GSV 4004B GPS receiver; (2), NovAtel dual frequency antenna; (3), Antenna cable (30 meter maximum); (4), Serial cable; (5), Power cable and (6), Personal computer running Linux.



Figure 5.1: The SCINDA GPS setup and installation

Chapter 6

Data and methodologies

Three data types are used in this thesis, Dst, SSN (sunspot number), and S4 and TEC data are used. The Dst and SSN data are available through the internet (world data center or WDC). But the TEC and S4 data are collected from scintillation network decision aid (SCINDA) GPS station installed at Addis Ababa and Bahir Dar. SCINDA is a network of ground based GPS receivers that monitors scintillations at the UHF and L-band frequencies in the equatorial ionosphere. These network of receivers are established by the US Air Force Research Laboratory (AFRL) and are monitored by this organization. In order to provide a more reliable situational awareness of scintillation impacts on users of space-based communication/navigation systems, L-band scintillation measurements from GPS satellites are ingested, in real time, to SCINDA. Its purpose is to aid in the specification and prediction of satellite communication degradation due to ionospheric scintillation in the equatorial region. Employing dual-frequency GPS observations, it is possible to calculate the estimates about GPS-derived ionospheric TEC. The GPS data recorded in the dual- frequency receivers have been utilized for this study, and the GPS-TEC data were obtained employing pseudo range and carrier phase measurements given in Eqs. 5.2.3-5.2.4. The final TEC value is obtained after the removal of the satellite and receiver biases using the following equations:

$$TEC = TEC_R - (b_R + b_S) \quad (6.0.1)$$

where TEC_R is relative TEC, b_R , b_S are receiver and satellite biased respectively.

$$TEC_R = TEC_\phi + (< TEC_P - TEC_\phi > ARC) \quad (6.0.2)$$

$$TEC_P = \frac{1}{40.3} \left[\frac{f_1^2 f_2^2}{f_1^2 - f_2^2} \right] (P_2 - P_1) \quad (6.0.3)$$

$$TEC_\phi = \frac{1}{40.3} \left[\frac{f_1^2 f_2^2}{f_1^2 - f_2^2} \right] (\phi_2 - \phi_1) \quad (6.0.4)$$

where TEC_P , the differential pseudo range; TEC_ϕ , the differential carrier phase; $<>ARC$, the average over phase connected arc. Calculating VTEC is possible by converting relative TEC:

$$VTEC = \frac{[TEC_R - (b_R + b_S)]}{S(\varepsilon)} \quad (6.0.5)$$

where $S(\varepsilon)$ is the single layer mapping function of the ionosphere defined as

$$S(\varepsilon) = \sec\left\{\sin^{-1}\left[\frac{R_e \cos(\varepsilon)}{R_e + h}\right]\right\} \quad (6.0.6)$$

where ε is elevation angle; R_e is the Earth's radius in kilometers; h is ionosphere height.

Using trigonometric identity, we can reduce Eq. 5.2.6 as follow.

$$S(\varepsilon) = \left(1 - \left[\frac{R_e \cos(\varepsilon)}{R_e + h}\right]^2\right)^{-\frac{1}{2}} \quad (6.0.7)$$

The Dst and SSN datas are loaded from <http://wdc.kugi.kyoto-u.ac.jp> (during 04/05/2015 07:37 pm) and <http://www.ips.gov.au/Solar/1/6> (during 04/05/2015 08:21 pm) respectively.

Chapter 7

Results and discussion

7.1 Solar Activity

The VTEC and S4 variability is determined by solar activities. The variations in VTEC and S4 also occurred due to the tilt and rotation of the earth around the Sun; the variation of solar zenith angle and intensity of radiation at any geographical location. Solar activity takes the form of solar wind acceleration, flux emergence, light and energy particles released from the Sun such as solar flares, coronal mass ejection or solar eruptions and coronal heating. However the most common and important measure of solar activity is sunspot number.

Sunspots are the physical expression of complex processes within the Sun and are seen as dark areas on the solar disk that wax (become stronger) and wane (become weaker). Sunspots are darker than their surrounding area because they are cooler than the average temperature of the solar surface and can therefore easily be observed. The appearance and disappearance of sunspots is due to underlying changes in the magnetic fields that exist throughout the Sun. The solar cycle has an average length of 11 years. However, cycles vary considerably in length from as short as 9 years up to almost 14 years. Due to its large day-to-day variability, the sunspot number (SSN) is usually averaged over a month. Figs. 7.1-7.2 show SSN time series covering the period from 2002 to 2014. The solar minima years of 2008-2010 and maxima years of 2012-2014 are clearly depicted in

Fig. 7.1. The maximum of solar cycle 24 was reached in February 2014, which reads

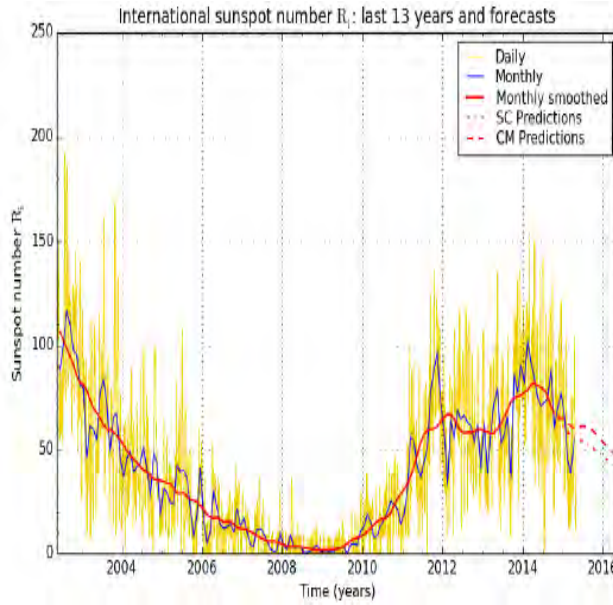


Figure 7.1: The solar activity (from [http : //sidc.oma.be/silso/dayssnplot](http://sidc.oma.be/silso/dayssnplot), Royal Observatory of Belgium 2015 May 4).

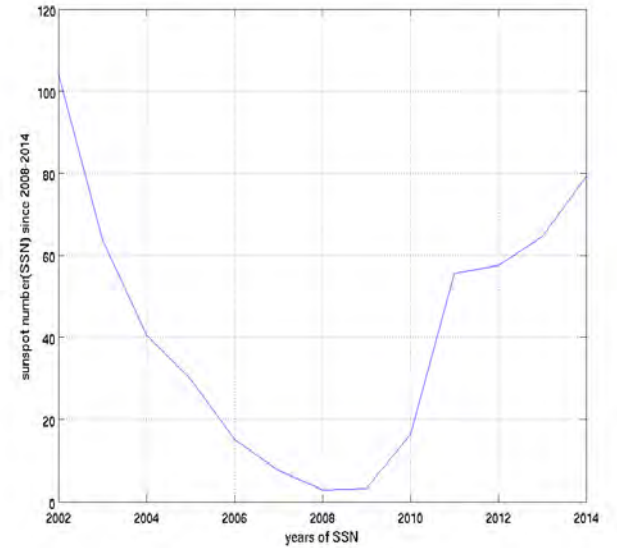


Figure 7.2: The interannual mean of SSN using data from [http : //www.ips.gov.au/Solar/1/6](http://www.ips.gov.au/Solar/1/6).

102.8. Similarly a moderate enhancement of solar activity is shown in November 2012 with peak of 96.7. The starting time of the solar cycle 24 was January 4, 2008, which covers the period used in this study.

7.2 Temporal variation of scintillation

Different storms may influence the behaviour of temporal variation of scintillation. As a result we select a days free from disturbance (quiet days) from world data center (WDC). The quiet days are March 7, 10, 25, 26, 2013. Fig. 7.3 shows VTEC values and S4 on these date. The peak values are attained nearly between 1000 and 1500 UT (1300 and 1800 LT). The VTEC minimum is at night, mostly at around 0300 UT (0600 LT). The minor enhancements and fluctuations of both VTEC and S4 in Fig 7.3 are the consequences of raising of the F2 layer to higher altitudes (where the recombination rate is smaller) by electric fields and by modulation of thermospheric winds. In addition, the equatorial

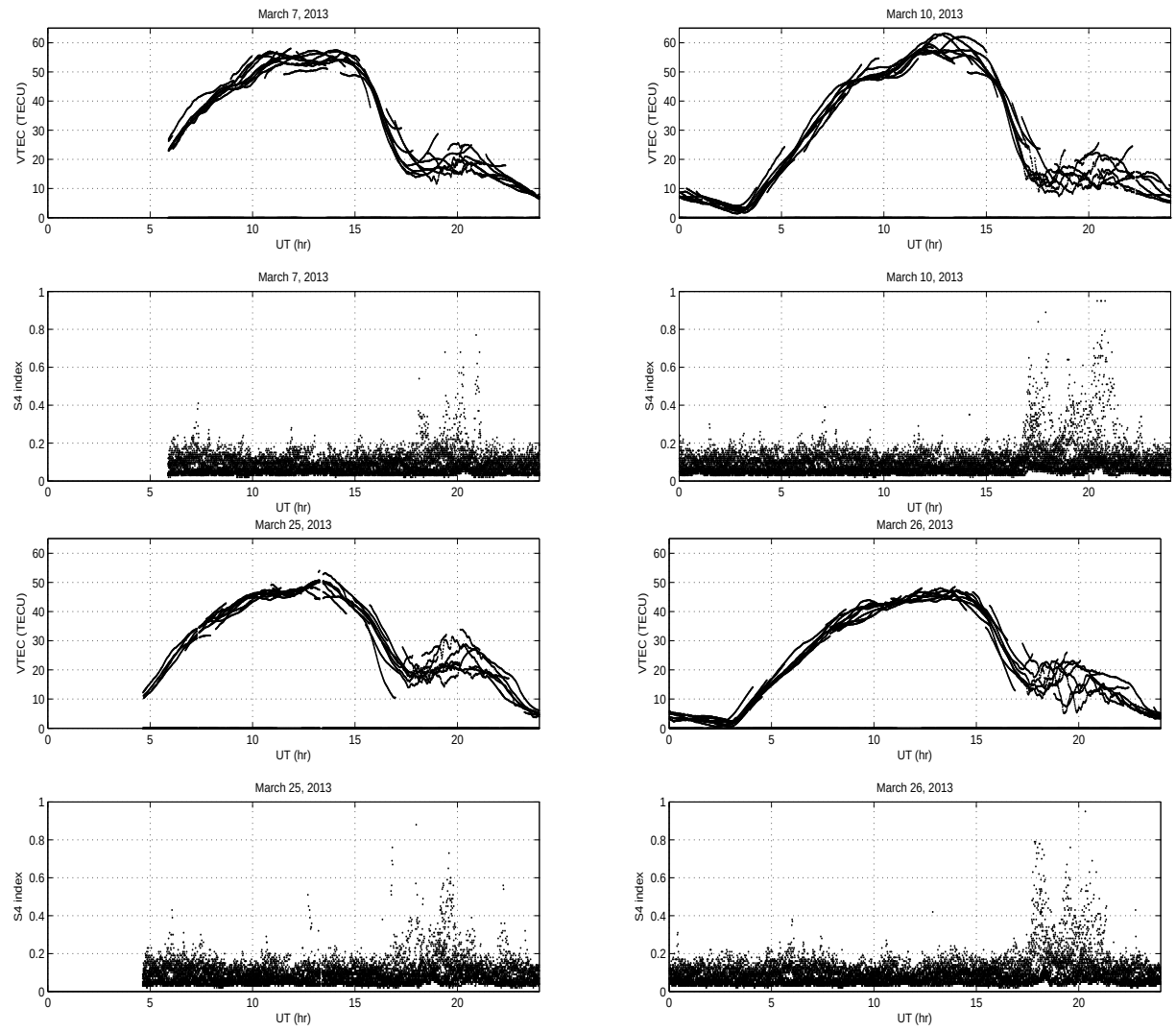


Figure 7.3: The temporal variations of VTEC over Addis Ababa, during quiet days on March 7, 10, 25, 26, 2013. The days are selected based on Dst index from world data center (WDC).

anomaly region, the most important source of such night time enhancement is the evening increase in the upward $\vec{E} \times \vec{B}$ drift at the equator[43]. Enhancement in S4 is observed during time when VTEC is at its lowest minima. Generally scintillation is enhanced during night while there is some variation from event on one day to the other. Observations in Fig. 7.3 are consistent with the fact that activity is highly determined by pre-reversal enhancement of TEC due to (Rayleigh Taylor Instability) phenomena during post-sunset.

7.3 Long term diurnal variation of VTEC and S4

Figs. 7.4-7.5 show the diurnal variations of the hourly mean VTEC values over Addis Ababa and Bahir Dar for all months through out 7 years. The hourly long term VTEC mean attains maximum at Addis Ababa and Bahir Dar throughout all seasons at the same time. The hourly long term S4 mean exhibit similar at both GPS sites. The hourly long term VTEC mean at Bahir Dar is higher than that at Addis Ababa. S4 long term hourly mean at the two stations have the same relationship. However, there is a slight shift in the time of occurrence of peak VTEC and S4 between the two stations. Bahir Dar leads Addis Ababa by about a fraction of hour.

7.4 Storm time characteristics of VTEC and S4

During the period under investigation (2008-2014) moderate geomagnetic storms have occurred during different times. Geomagnetic storm of January 2012 has been investigated by other authors. Therefore, in this thesis we focus on a relatively weaker storm in september 2011. There were a series of storms that have occurred in September with DS_T index -102 nT on September 27, 2011, -86 nT on September 17, 2011. The corresponding observations of VTEC and S4 show that there were enhancement in VTEC on September 17, and 27. However, there was enhancement in S4 on September 17 while there was inhibition of S4 on September 27 (Fig. 7.6).

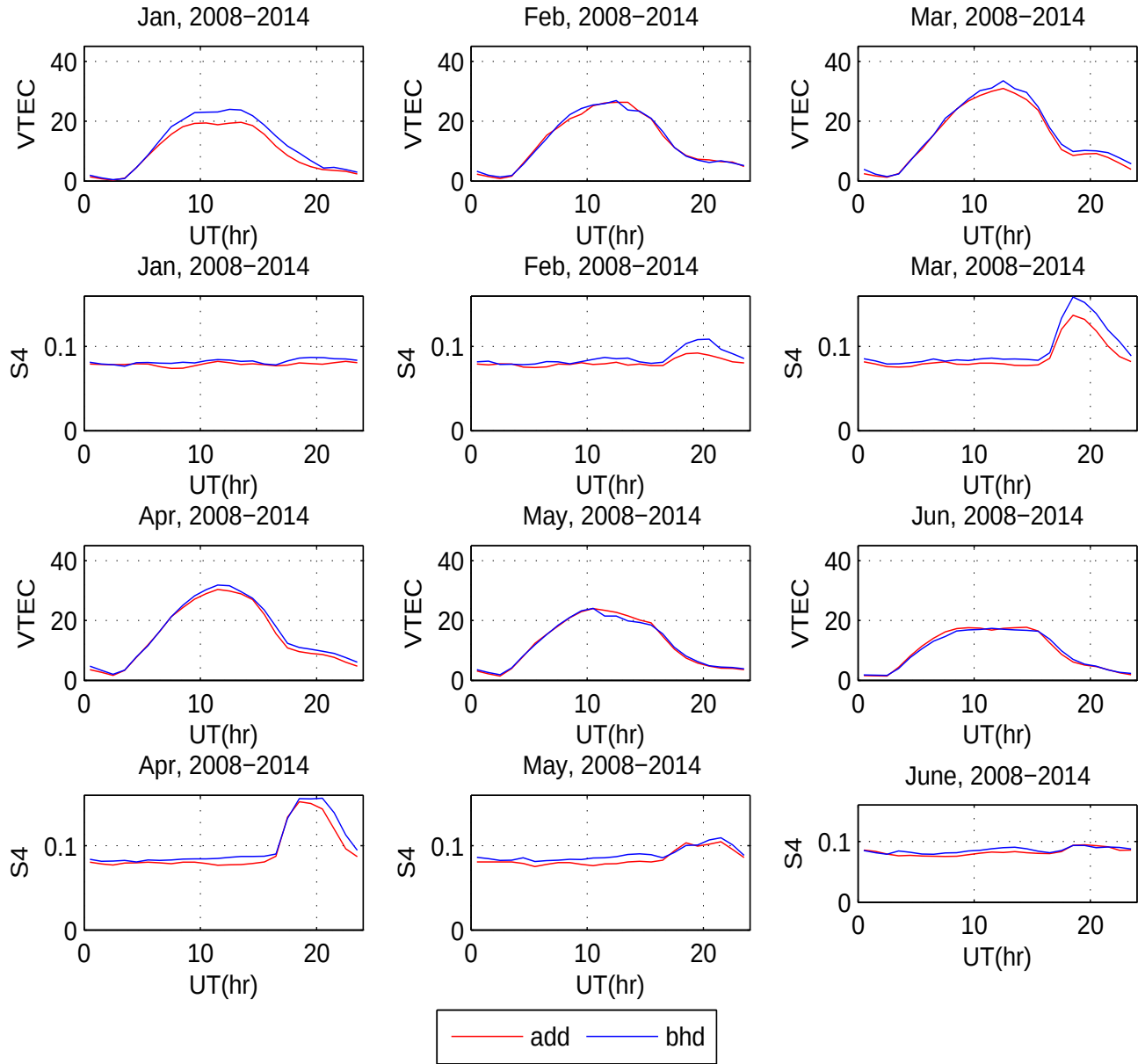


Figure 7.4: Long term mean (2008-2014) of hourly VTEC and S4. First row : VTEC for January to March; second row: S4 for January to March; third row: VTEC for April to June; last row: S4 for April to June Addis Ababa GPS site (red) and Bahir Dar GPS site (blue).

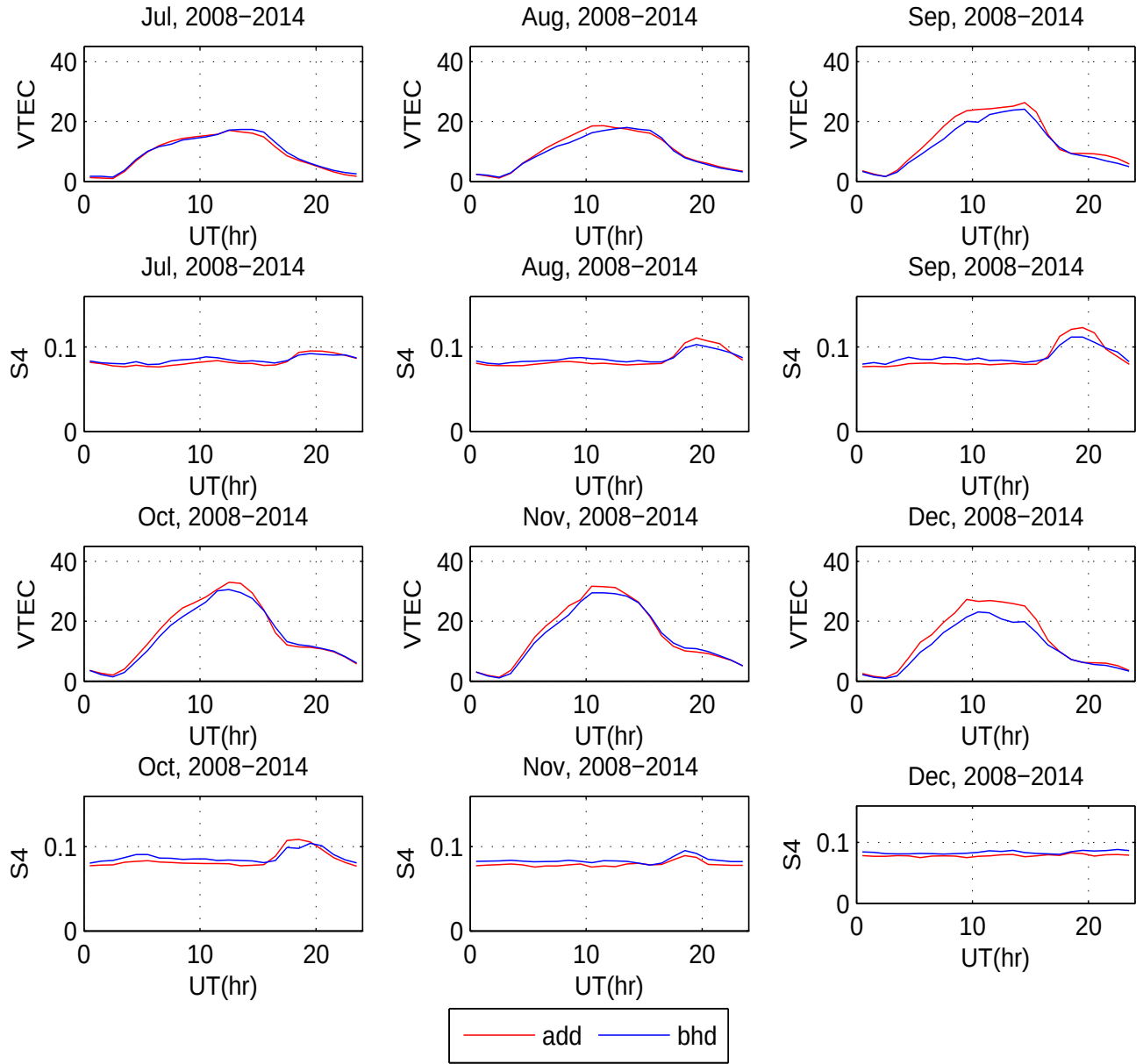


Figure 7.5: Long term mean (2008-2014) of hourly VTEC and S4. First row : VTEC for July to September; second row: S4 for July to September; third row: VTEC for October to December; last row: S4 for October to December, Addis Ababa GPS site (red) and Bahir Dar GPS site (blue).

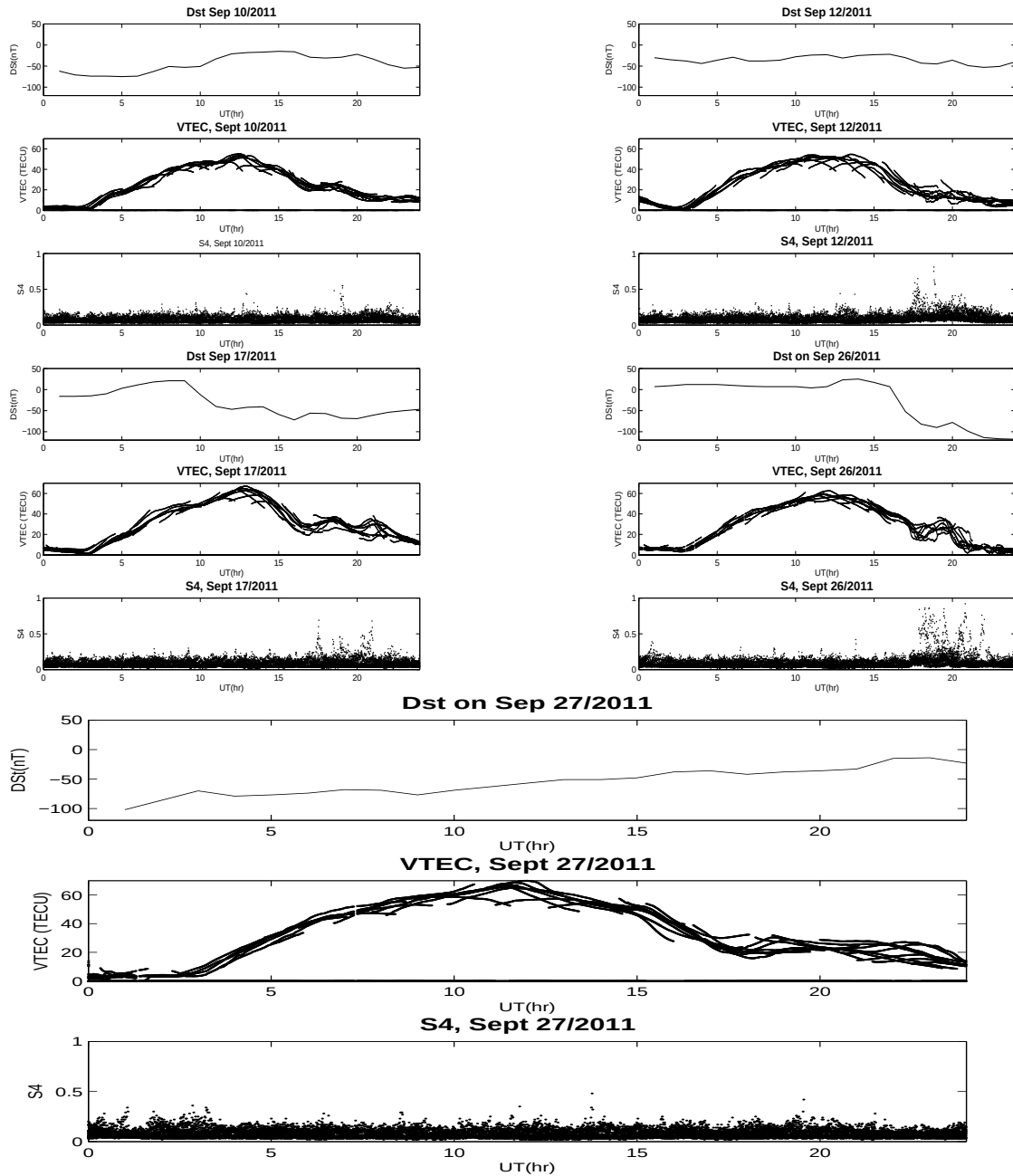


Figure 7.6: VTEC, S4 and Dst index diurnal Variation for selected storm days on September 10, 12, 17, 26 and 27, 2011.

7.5 The impact of observation geometry on S4 index for arbitrarily selected GPS and days of observation

Elevation angle is the angle between the horizon plane and the coming inclined ray or line of signal where the receiver exists and the direct path of signal from satellite to receiver.

The scintillation increases when the PRN satellites elevation angles becomes low and vice versa at Addis Ababa (Fig. 7.7) and Bahir Dar (Fig. 7.8). For instance, when elevation angle of PRN 26 Satellite is about 80° , S4 is reduced to very low value 0.03 at around 15 UT hours (Fig 7.7, top left). On the contrary, S4 is enhanced for PRN 05 when elevation angle is 15° at around 17 UT hours.

7.6 VTEC and S4 seasonal variability

Fig. 7.9 depicts VTEC and S4 for Addis Ababa during low solar activity (blue) and maximum phase solar activity (red). Enhanced scintillation has occurred during E season (Fig. 7.9, middle column, bottom panel). This is followed by J-season. Moreover, the most enhanced VTEC during maximum solar activity period occurred during E season followed by D-season.

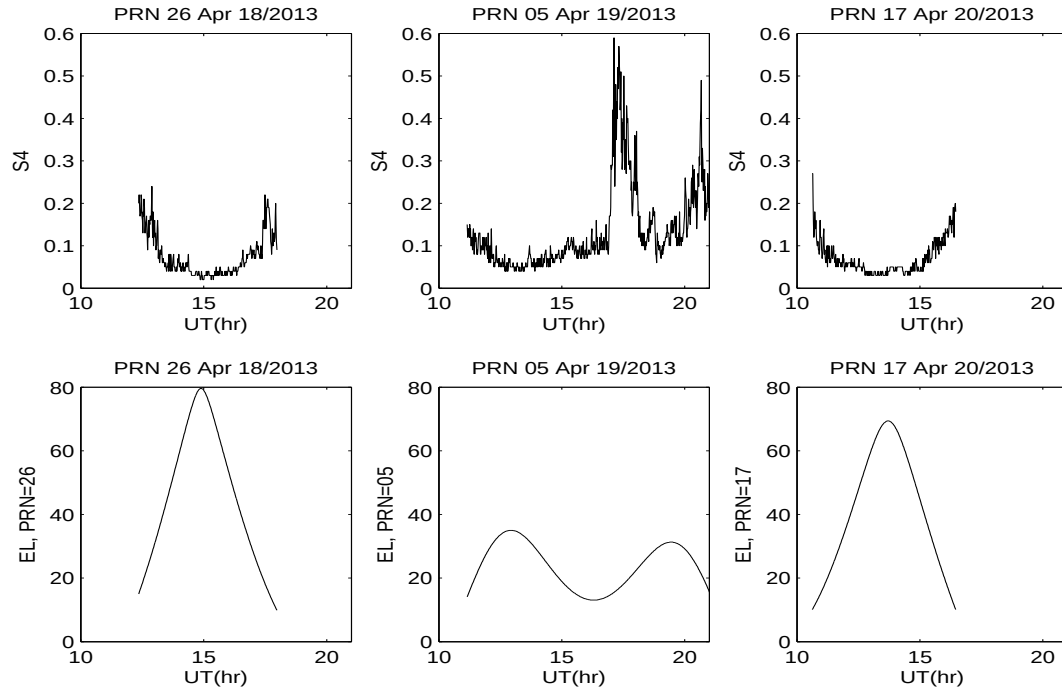


Figure 7.7: The influence of PRN elevation angle on Scintillation occurrence at Addis Ababa.

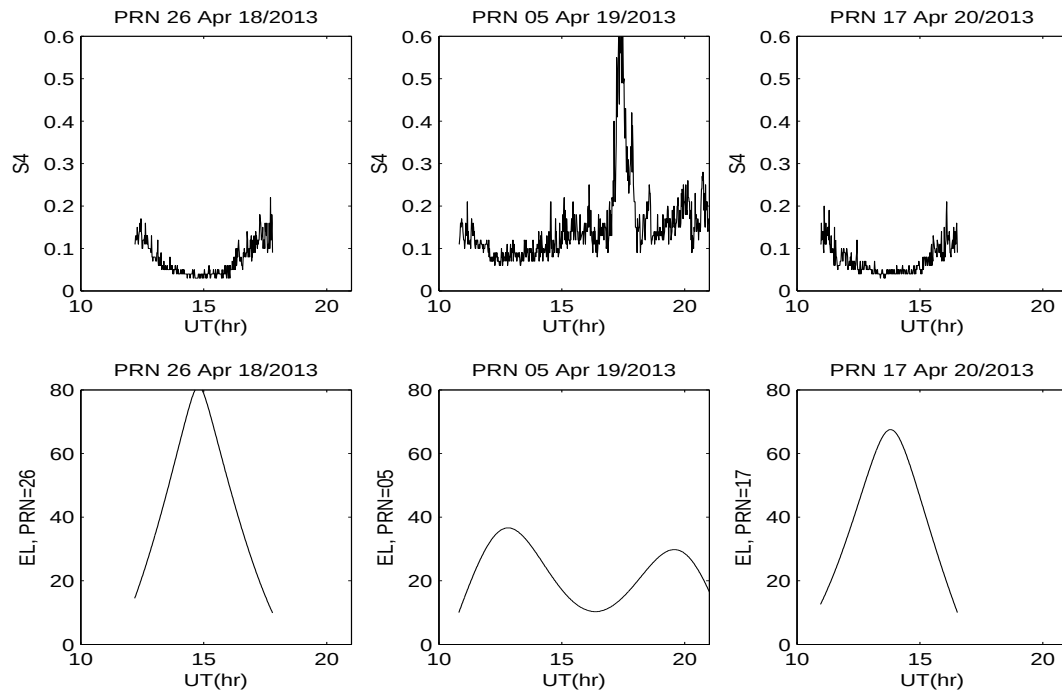


Figure 7.8: The influence of PRN elevation angle on Scintillation occurrence at Bahir Dar.

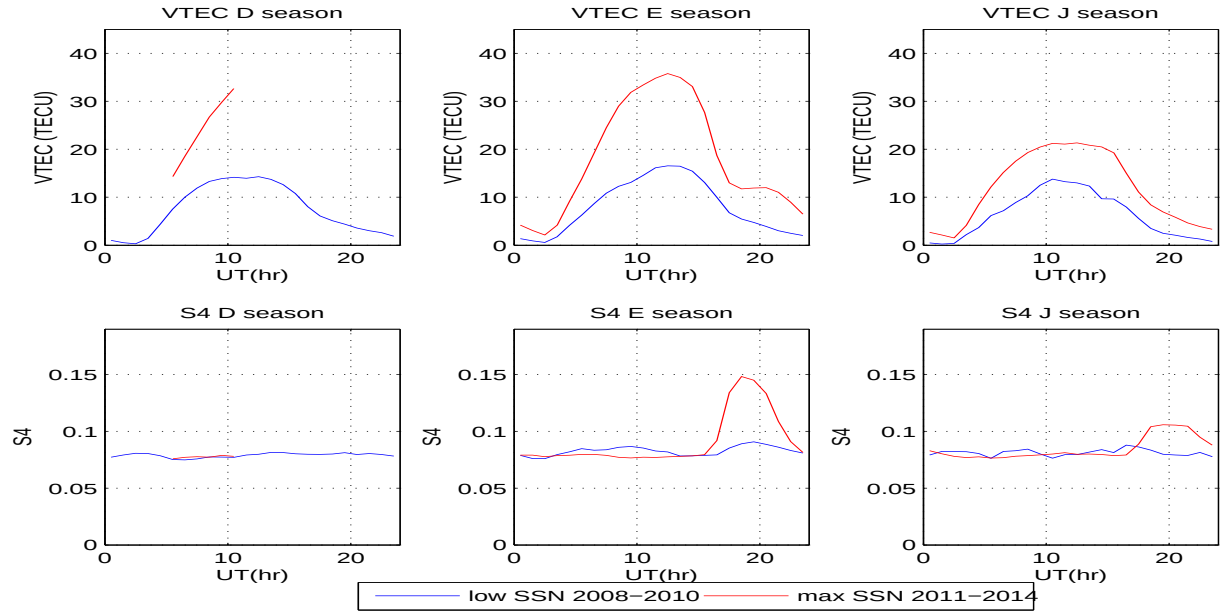


Figure 7.9: Seasonal mean during low solar activity (2008-2010) and high solar activity period (2011-2014). Top row VTEC and bottom row S4.

7.7 Long term mean variation of D, E and J season VTEC and S4

Fig. 7.10 shows the enhanced VTEC and S4 during E-season over Addis Ababa and Bahir Dar. D-season VTEC is the next maximum TEC while J-season is the next S4 maximum to E-season. This is because scintillation could be initiated during rain J-season at equatorial latitudes [44]. The maximum enhanced VTEC was 30 TECU at 1300 UT in both Addis Ababa and Bahir Dar, minimum VTEC was less than 5 TECU at around 003 UT. The slightly difference in VTEC and S4 over Addis Ababa and Bahir Dar may due to difference in geographical latitude.

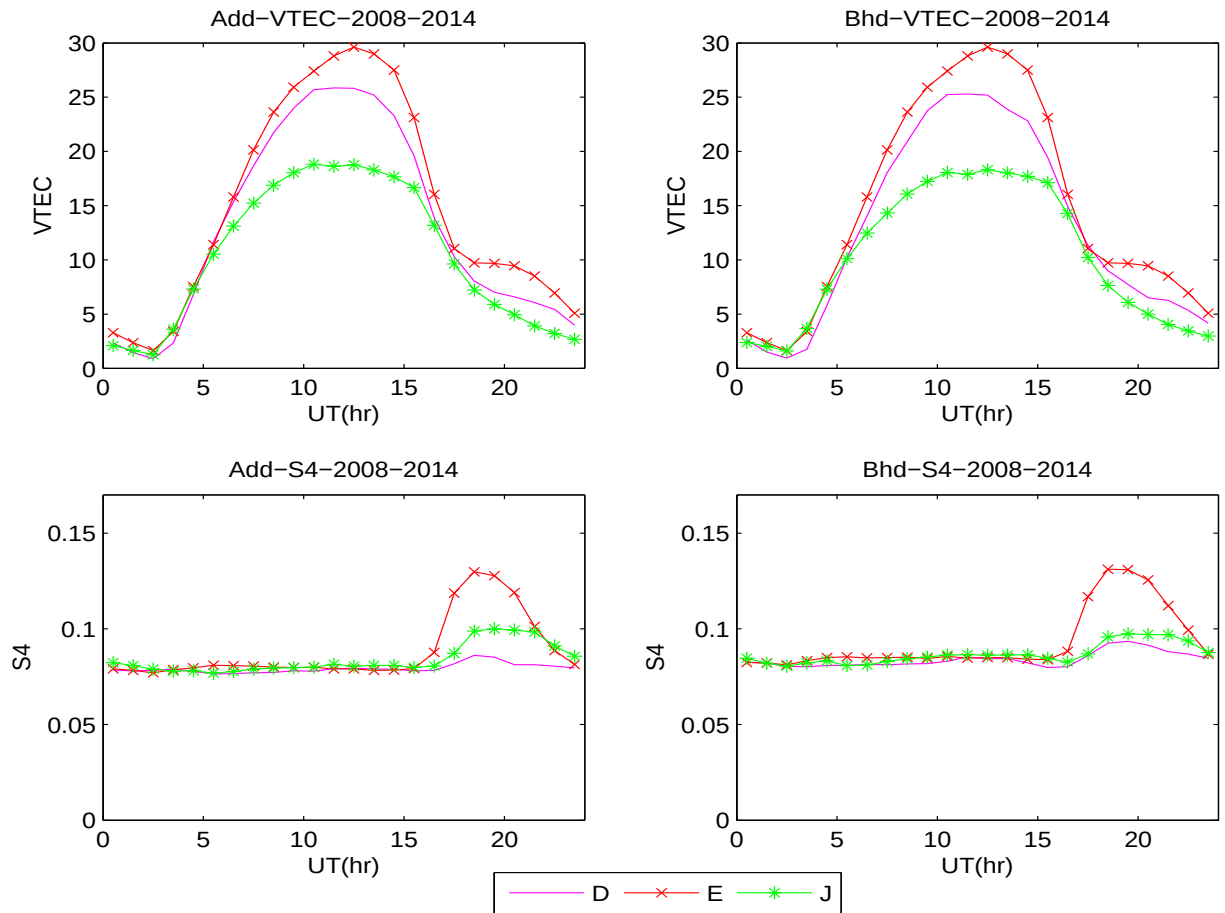


Figure 7.10: Long term mean variation of D, E and J seasons VTEC and S4 over Addis Ababa (first column) and Bahir Dar (second column).

7.8 Interannual variation of seasonal mean VTEC and S4

The VTEC for D, E and J-season increases from solar minimum (2008) to maximum (2014) (Fig. 7.11). However, despite on general increase in scintillation from 2008 to 2014, there was a break in 2013 for D and E season due to decrease in S4.

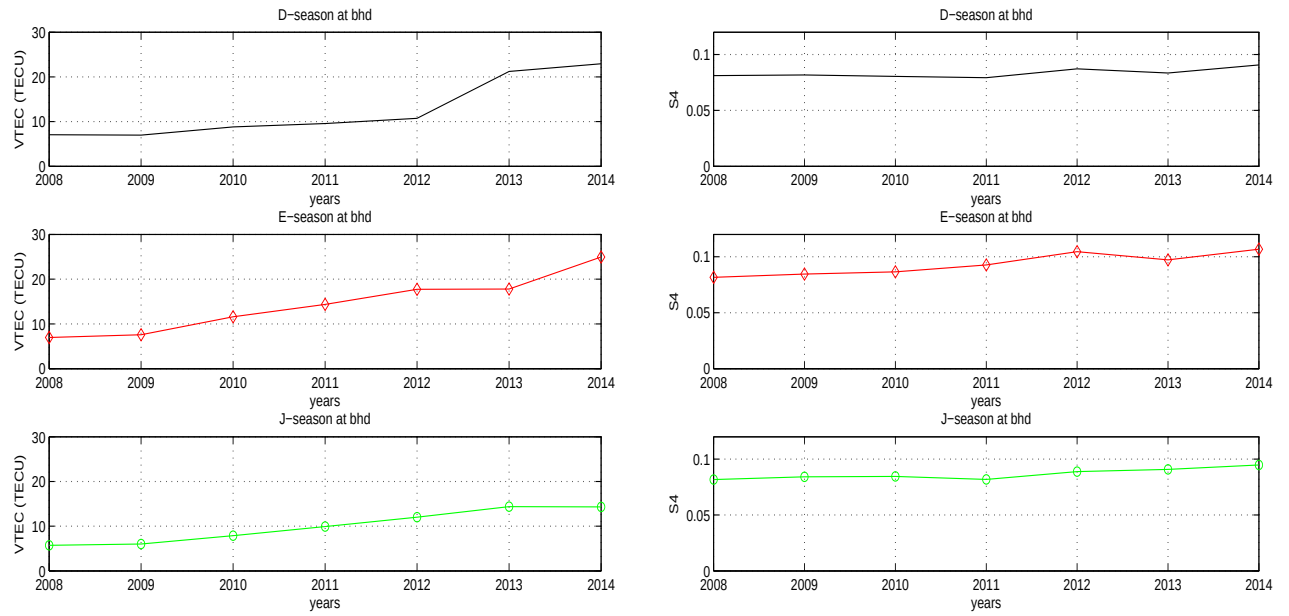


Figure 7.11: Interannual variability of VTEC and S4 for first and second column respectively over Bahir Dar.

Chapter 8

Conclusions

The 2008-2014 period lies in solar cycle 24. The enhancement in S4 is closely linked with pre-reversal enhancement of VTEC at both Addis Ababa and Bahir Dar. The most enhanced S4 occurred just before mid-night in almost all cases investigated in this work.

Long term hourly mean of VTEC and S4 attain their maximum values at noon and promidnight at both Addis Ababa And Bahir Dar. However, VTEC and S4 maxima at Bahir Dar are higher than Addis Ababa and occur slightly at earlier time.

The investigation shows that September, 2011 is a period when a series of weak to moderate geomagnetic storms have occurred. The storm time characteristics of VTEC and S4 are such that VTEC is slightly enhanced compared to quiet period while there is no clear evidence on the difference between storm and quiet time S4 values.

Consistent with previous studies, observations of S4 at low elevation angles show that S4 is highly enhanced at both Addis Ababa and Bahir Dar GPS Stations.

The seasonal variability in VTEC and S4 is characterized by enhanced scintillation and VTEC during E-season. This follows similar features in long term mean variation. The VTEC and S4 generally increases from solar minimum to maximum period with exception in 2013 for S4 in D and E season.

In summary, we have investigated VTEC and S4 characteristics over a period of 7 years at Addis Ababa And Bahir Dar using high resolution SCINDA GPS observations for the first time to our knowledge.

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Declaration

This thesis is my original work, has not been presented for a degree in any other University and that all the sources of material used for the thesis have been dully acknowledged.

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