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IONOSPHERIC ELECTRON CONTENT AND L BAND SCINTILLATION STUDY IN THE SOUTH PACIFIC REGION USING GPS

By

Ramendra Prasad

A thesis submitted in fulfillment of the requirements for the degree of Master of Science in Physics

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School of Engineering and Physics
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November 2012
Declaration

Statement by Author
I, Ramendra Prasad, declare that this thesis is my own work and that, to the best of my knowledge, it contains no material previously published, or substantially overlapping with material submitted for the award of any other degree at any institution, except where due acknowledgement is made in the text.

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Dedication

To my parents

Mr. Mahendra Prasad and Mrs. Sudha Prasad

and my wife Mrs. Sarita Prasad
Acknowledgements
I would like to take this opportunity to thank all those individuals and organizations that have contributed to the successful completion of this thesis. I wish to present my sincere gratitude and appreciation to my supervisor Dr. Sushil Kumar for his guidance and patience throughout this project. His constant monitoring and the valuable advices ensured the completion of this thesis. I thank him in motivating me to do my best.

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Abstract

The total electron content (TEC) and L1-band ionospheric scintillations recorded using GSV 4004B GPS Ionospheric Scintillation and TEC monitor (GISTM) data acquisition system during 2010-11 have been analyzed to accomplish the scientific objectives of this work. The TEC recorded by the receiver at different elevation angles of the GPS satellites were slant TEC (STEC) values which were then converted to vertical TEC (VTEC) to remove the biases induced by different elevation angles. The diurnal, monthly, seasonal and annual TEC variations as well as day-to-day TEC variability on magnetically quiet and disturbed days were studied. The diurnal variation revealed TEC maximum at around 14:00 LT and minimum between 02:00-06:00 LT. Monthly variation showed maximum VTEC in the months of December and minimum in June and August. The day-to-day variability study in TEC showed maximum variability in the daytime between 12:00-15:00 LT followed by pre-midnight and least variability during post-midnight period between 04:00-06:00 LT. The day-to-day variability in VTEC could have been due to various factors such as EUV flux, geomagnetic activity, local temporal conditions in the thermosphere, variation in thermospheric neutral composition, variation in neutral winds, influence of solar dynamic processes, atmosphere-ionosphere coupling, vertical coupling resulting from atmospheric waves like gravity waves and tides or planetary waves, the equatorial electrojet (EEJ) generated by atmospheric tides and meteorological factors. Seasonal analysis showed higher TEC during the hot and wet season as compared to the cold and dry season. The cold and dry seasonal average, showed a diurnal plateau from 09:00 to 16:30 LT whereas during hot and wet season, no significant plateau was observed, but a distinct crest occurred at around 14:45 LT.

L-band amplitude scintillations were examined for their morphological study at Suva. The GSV 4004B receiver records scintillation index $S_4$, on L1 signal and the correction to $S_4$ ($S_4$ Cor) due to multipath effects. The final $S_4$ ($S_4$ FIN) values were computed by subtracting the $S_4$ Cor from the recorded $S_4$ in a Random Sum Spectrum (RSS) sense. This $S_4$ FIN has been used to categorize weak ($0.2 \leq S_4 < 0.3$), moderate ($0.3 \leq S_4 < 0.45$) and strong ($0.45 \leq S_4$) scintillation events and then the monthly and seasonal percentage occurrences of different category of scintillation events were
studied. Out of a total of 480 events, 84.4% were weak, 14.6% were moderate and 1% were strong, according to the above category. The amplitude scintillations were most pronounced in the daytime with January showing the highest number of events. Seasonal analysis revealed that scintillation events were more often during the hot and wet season as compared to the cold and dry season. Annually, scintillations occurred mostly in the daytime with peak occurrence at around 05:00-09:00 LT. Daytime strong scintillation events were not associated with TEC depletions and phase scintillations, but the signal to noise ratio during the scintillation events decreased with increase in $S_4$. However, post-midnight strong amplitude scintillations were associated with TEC depletion and phase scintillations indicative of large scale irregularities.

Geomagnetic disturbances effects on TEC and scintillations were studied by separating these on the five quiet (Q) and disturbed (D) days in every month. It has been found that TEC is higher on D-days when compared to Q-days. The day-to-day variability in TEC is also higher on D-days. Seasonally, scintillation activity was more pronounced on D-days as compared to Q-days. The TEC and scintillations were also analyzed under the moderate (-100 nT ≤ $Dst$ < -50 nT), intense (-200 nT ≤ $Dst$ < -100 nT) and very intense ($Dst$ < -200 nT) storms. The storms were grouped according to the occurrence times of their main phase into category A (daytime), B (pre-midnight) and C (post-midnight). A total of 17 storms occurred during two years, 2010 and 2011, out of which 14 were moderate and 3 were intense, while none were very intense. The effect of magnetic storms on TEC indicated: for category A storms (7 storms of all strengths; moderate, intense and very intense), TEC increase was mostly recorded during the main and recovery phases. For category B storms (3 storms of all strengths; moderate, intense and very intense), during the main phase VTEC increased and during the recovery phase the VTEC either increased or decreased. For category C storms (7 storms of all strengths; moderate, intense and very intense), 71.4% (5 out of 7) storms showed an increase in VTEC during the main phase while 28.6% (3 out of 7) showed a decrease. During the recovery phase 42.9% (3 out of 7) storms showed increase in VTEC and 57.1% (4 out of 7) showed no change in VTEC. Generally, in the entire three categories (A, B, C) of storms the post-storm scintillations were slightly enhanced.
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1.0 Introduction

Satellite communication is hampered by complex physical processes occurring in the ionosphere, mainly in the F-region. Due to the dynamic nature of the ionosphere there are irregularities formed within it which cause scintillations or fading on trans-ionospheric signals. As our dependence on satellites for communication, entertainment, scientific applications and navigation (like GPS) has been increasing, the study of ionosphere and fluctuations, on trans-ionospheric signals (scintillations) on regional and global scale has become very vital.

Ionospheric scintillation is defined as the fluctuation in the signal as it passes through the irregularities present in the electron content of the ionosphere [Basu and Basu, 1989]. Two areas of the globe troubled by intermittent scintillations are i) a 20° wide belt of latitudes around the geomagnetic equator and ii) the belt lying between sub-auroral to polar latitudes [Aarons, 1982]. The region i) of the globe is referred to as Equatorial Ionization Anomaly (EIA) where the total electron content (TEC) and scintillations are very much dependent on the local time of the day, the season, solar and geomagnetic activities. The South Pacific Region falls into this first belt, therefore the locations like Fiji provides unique opportunity for conducting scientific experiments (like use of GPS) to study characteristic variations in TEC and scintillations that are of utmost importance for existing and future planning of satellite links.

A number of different frequency bands like C (4 – 8 GHz), Ka (27 – 40 GHz) and Ku (12 – 18 GHz) are being used by satellites for practical and scientific purposes. The Global Positioning System (GPS) that has been used in this study for the TEC and scintillations uses the L-band (1-2 GHz). GPS currently transmits at 1575.42 MHz designated L1 band and 1227.60 MHz designated L2 band and is mainly used for precise point measurement at the Earth’s surface. GPS is also used to obtain meteorological parameters like precipitable water vapor [Troller, 2004]. The main advantages of applying this technique to study the upper atmosphere are that GPS signals could easily be received at any part of the globe and the system is cost-effective. In addition, a multiple channel receiver, as the one used in this project, simultaneously observes in different directions making it possible to map the ionosphere better.
1.1 Ionosphere

The ionosphere, a part of the Earth’s upper atmosphere, contains partially ionized plasma that is continuously changing under the influence of extreme ultra violet (EUV) radiation, recombination, neutral winds and electric field [Rishbeth and Gariot, 1969]. The ionosphere has sufficient electron content to support terrestrial communication up to high frequency (HF) and can disturb the trans-ionospheric communication [Dabas et al., 2006]. It extends from a height of above 50 km and overlaps the ozonosphere to over 1000 km [Kelly, 1989]. Ionospheric plasma is non-homogenous, anisotropic, dispersive, weakly ionized, magnetized, cold and collisional. Peak electron densities in the ionosphere vary greatly with time (diurnal, seasonal and sunspot cycle), geographic location (polar, auroral zones, mid latitudes and equatorial regions), and certain solar related ionospheric disturbances [McNamara, 1985].

Edward Appleton in 1927 discovered the existence of at least two separate ionized layers that he subsequently named E (for electric) and F (for field). The term ionosphere was introduced by Watson and Watt in 1929 [Rishbeth and Gariot, 1969]. Based on the electron density profile, the ionosphere is divided into D, E, F-regions which occupy the heights varying approximately from 70-90 km, 90-150 km, and 150-1000 or so km respectively. The F-layer is further divided into F1- (150-210 km) and F2- (over 210 km) layers during the daytime [Kelly, 1989]. The typical electron density structure of day and night time ionosphere is shown in Figure 1.1.

**D-REGION:** This region is only present in the day and is the lower most layer extending from 70-90 km from the surface of the Earth. The quiet time D-region is produced by the photo-ionization of NO by the most penetrating Lyman α radiation at a wavelength of 121.5 nm. During active phase of solar activity with 50 or more sunspots, hard X-rays with wavelength < 1 nm ionizes the air (N₂, O₂). During the nighttime cosmic rays produce ionization and the electron density of this region varies from 10⁸-10⁹ m⁻³. High energy electron precipitation is a source of D-region ionization in the auroral region.

High frequencies (HF = 3-30 MHz) pass through this layer, while the low frequency waves (LF = 30-300 kHz) are absorbed by this layer. The absorption is due to
Chapter 1  Introduction

The layer being weakly ionized and having a very high ion-neutral collision frequency [Riberio, 2011]. Extremely low frequency (ELF = 3 Hz-3 kHz) and very low frequency (VLF = 3-30 kHz) are reflected and also partially absorbed by the D-region.

**E-REGION:** The E-region extends from 90-150 km and undergoes a large day-to-night variations. This has daytime electron density of about $10^{11}$ m$^{-3}$. The E-region remains throughout the night with decreased electron density of about $5 \times 10^9$ m$^{-3}$. The most extensively found positive ions in this region are $O_2^+$ and $NO^+$ that are produced by the X-rays with wavelength of 1-10 nm and the UV radiation. In this region strong electric currents are generated by the dynamo effect [Ratcliffe, 1972]. It reflects radio waves with frequencies less than about 10 MHz and deteriorates the signals above 10 MHz as it partially absorbs these waves.

**F-REGION:** Above the E-region lies the F-region. The plasma density in the F-region increases with altitude up to about 300 km and then decreases. The electron density in this region is in order of $10^{12}$ m$^{-3}$ in F-peak. The F-region splits into F1- and F2-regions during the daytime. The F-region plays a vital role in the High frequency (HF) communications since it contains the largest concentration of electrons. The dominant ion is $O^+$. At daytime the F1-layer is able to reflect radio waves up to wavelengths of about 30 m. The F2-layer is characterized by having large electron density with a maximum approximately at 300-400 km altitude. Therefore, F-layer engenders the largest effect on trans-ionospheric communications.

However, a few hours after the sunset, the F1-region becomes very much depleted and the F1- and F2-layers merge to form the F-layer in the nighttime. This condition of high density plasma on top of low density plasma is very unsteady and if the equilibrium is disturbed, then irregularities are generated.

In addition to the variation of the plasma density with altitude, the ionosphere also shows significant variations with time of day, latitude, longitude, season, solar activity, and geomagnetic activity. A distinctive latitudinal variation in the ionosphere is created owing to the geometry of the Earth's dipolar magnetic field lines. The ionosphere, therefore, is classified into three latitude regions, low-latitude or equatorial region ($< 20^\circ$ magnetic latitude), mid-latitude zone ($20^\circ - 55^\circ$), and high-latitude (auroral) regions ($55^\circ - 90^\circ$). These regions are controlled by different physical processes
and thus considerable different ionospheric conditions exist in these regions. In the following sections, the discussion will be limited to the low latitude ionosphere, since my dissertation focuses on this region only.

![Illustration of Day and Night Structure of the Ionosphere](Australian Space Weather Agency, 2011)

**Figure 1.1:** Day and night structure of the ionosphere

**EQUATORIAL IONOSPHERE:** The equatorial ionosphere is unique in its characteristics since the geomagnetic field is horizontal over it. A number of fascinating phenomena; Equatorial Electrojet (EEJ), Equatorial Spread F (ESF), Equatorial Sporadic E and the Equatorial Ionization Anomaly (EIA) arise in this region.

The equatorial ionospheric electric field $\mathbf{E}$ is eastward during the day and westward during the night. Since the geomagnetic field $\mathbf{B}$ is northward and horizontal, it gives rise to an $\mathbf{E} \times \mathbf{B}$ drift which is upwards during the day and downwards during night. The upward drift drives the plasma across the magnetic field lines to higher altitude. This physical mechanism is called the “fountain effect” as shown in Figure 1.2. The transfer of plasma takes place from equatorial region to higher latitudes [Heredia and Elias, 2004] giving rise to the EIA or “Appleton anomaly” [Belly and Alcayde, 2007]. This plasma then diffuses downwards along the magnetic field lines under the influence of gravity and pressure gradient forces resulting in ionization enhancements on both
sides of the magnetic equator at about ±15° to ±20° in the geomagnetic latitude [Klobuchar, 1991]. It has often been found that an asymmetry exists between the northern and southern anomaly. Due to an inter-hemispheric wind blowing from the summer to the winter hemisphere, plasma moves upward along the geomagnetic field lines in the summer hemisphere, while plasma moves downward in the winter hemisphere. Therefore, the transport of the lifted plasma toward the winter hemisphere is enhanced, and the plasma transport towards the summer hemisphere is decreased. As a result, the equatorial anomaly in the winter hemisphere is generally larger than in the summer hemisphere [Bhuyan and Bhuyan, 2007; Hawlitschka, 2009].

![Figure 1.2: The fountain effect and formation of equatorial anomaly. Reproduced from Groves [2004].](image)

Figure 1.3 shows the equatorial anomaly regions on both the sides of the geomagnetic equator. Our TEC and scintillation measurement site Suva (18.15° S, 178.45° E. Geomagnetic latitude 21.07° S) lies well within the Equatorial Anomaly as indicated in the Figure 1.3.
During the night, the electric field is westward and the $E \times B$ drift is downward. However, just before this electric field reversal takes place, the upward drift rapidly increases, pushing the F-layer to higher latitudes. This large upward drift is opposed to the gravity and combined with other factors creates a very unstable configuration [Kelly, 2009] which is referred to as pre-reversal enhancement (PRE). During the daytime, the F-region dynamo fields driven by the F-region winds get short circuited. However, near sunset the conductivity decreases suddenly and sets up a large polarization field in the F-region which results from field-aligned currents between the E- and F-regions [Oyekola, 2007]. Consequently, this F-region dynamo field induces rapid pre-reversal enhancement in the anomaly gradients. The PRE has been observed during 19:00-22:00 LT and the morning reversal occurs between 05:00-06:00 LT [Ramarao et al., 2006b; Oyekola, 2007; Fejer et al., 2008]. This morning reversal is conducive for the generation of Equatorial Spread-F (ESF) [Ramarao et al., 2006a].

In addition, the production of ions ceases after sunset and the conduction of the lower ionosphere decreases dramatically, thus in the bottom side of the F-layer, an unstable configuration is created. This triggers the production of “plasma bubbles” [Sekar and Chakrabarty, 2008] which are regions of large electron density depletions in the equatorial ionosphere [Zalesak, 1983]. The development of the plasma bubbles begins on the bottom-side of the ionospheres which buoyantly rise and eventually penetrate to the topside of the ionosphere. These irregularities known as ESF are
generated through the collisional Rayleigh-Taylor mechanism driven by gravity [Zalesak, 1983]. Through the Generalized Rayleigh-Taylor instability (GRT) mechanism, the bubbles with depleted plasma density are uplifted to higher altitudes and at the same time small scale irregularities grow on large scale gradients in plasma bubbles through secondary instabilities. As the plasma-depleted bubble rises from the bottom-side of the F-layer, they get elongated along the field lines to off equatorial latitudes and extend up to a north-south dimension of the order of 2000 km [Zalesak, 1983; RamaRao et al., 2006a].

When these plasma bubbles come into line-of-sight between the receiver and the satellite, the radio frequency propagating through this undergo the highest disruptive levels of scintillation, both in amplitude and phase levels [Ramarao et al., 2006b].

The ionosphere is highly dynamic and dependent on the input energy from the Sun. It has great temporal variability ranging from minute (during geomagnetic storms) to 11 years solar cycle and remarkable spatial variability that depends on the geometry of the Earth’s magnetic field [Klobuchar, 1991]. In addition to this, ionospheric plasma irregularities drifting in front of the satellite radio signals, scintillate the radio wave signals and causes unevenness of the signals at the receiver end. Therefore, the behavior of the ionosphere under different geophysical conditions at different geographical locations needs to be understood carefully. The present study is centered on the behavior of the ionosphere and scintillations during various conditions like day, night, seasonal and geomagnetic disturbances as well as the geomagnetic storms.

1.2 Ionospheric Irregularities

The ionospheric plasma as discussed earlier is non-homogenous, dynamic, and in continuous motion as a result of neutral winds and electric field. In addition, the plasma in space is also not in its thermo-equilibrium state, so in order to come to a true equilibrium, the plasma needs to shed some of its energy to some wave modes. In doing so, the amplitude of the plasma grows with time and this growing plasma wave is called an unstable mode. In other words, the plasma instability is a process whereby the free energy of the plasma gets converted into a growing mode in a collective way [Bagiya, 2010]. These instabilities create fluctuations and structures in the plasma density which
is known as irregularity [Guzdar et al., 1981]. The irregularities are found at all latitudes of the globe with scale sizes varying from centimeters to kilometers. The ionospheric irregularities have been clustered into E- and F-region instabilities or irregularities.

**E-region irregularities:** The E-region irregularities are commonly known as Sporadic-E layer or Es. The Es is characterized by a thin reflecting layer in the ionosphere which comes and goes sporadically at E-region altitudes of 100-120 km where the ion motion is controlled mainly by collisions with neutrals [Bhattacharya, 1991]. Es usually consists of metallic ions. Weaker forms of Es consist of cloud of ionization and the most intense forms consist of a thin sheet of ionization some tens or hundreds of meters in thickness which can vary from 0.5-5 km and the horizontal extent can vary from 10-1000 km [Wu et al., 2005]. Es is observed on ionograms as an echo at constant height which extends to a higher frequency than usual critical frequency of the E-region.

The Es is observed at all the latitudes, however, the strongest and more frequent layers occur at the mid-latitudes since the two ion convergence mechanisms (zonal wind shear and meridional wind shear) does not work efficiently at the magnetic equator and in the auroral zones [Wu et al., 2005; Farley, 2009; Haldoupis, 2011]. Es occurs through the mechanism of wind shear theory, whereby the East-West winds in the E-region causes a vertical movement, compressing the ions into thin layers of high density. The wind shear theory, proposed by Whitehead [1961] relies on the process of vertical shear in the horizontal wind which in the presence of Earth’s magnetic field forms a layer of ionization, the Es [Kagan and Kelley, 1998; Haldoupis, 2011]. As discussed earlier, the ionosphere over equatorial and low latitudes is very strongly influenced by the Earth's magnetic field. Usually, it is more useful to consider how the ionosphere varies with geomagnetic latitude or with dip angle of the Earth's magnetic field rather than within a geographic framework. Es formed in the equatorial region is known as the Equatorial Sporadic-E (Esq). Esq has been found to be formed due to plasma instability caused by the high electron drift velocity associated with Equatorial Electrojet (EEJ) [Rastogi, 1972] and is present during both day and night even when the electron densities are greatly reduced [Bhattacharya, 1991]. Generally, Es appears as patchy and mostly
transparent region, while sometime it appears in sheet which can completely cover the overlying F-region.

Radar spectral studies have revealed two distinct types of irregularities; Type I and Type II. Type I occurs only when the electrojet current exceeds some minimum value. These irregularities travel with a phase velocity equal to the ion-acoustic speed and are thought to be generated by the excitation of the two-stream instability. The Type I irregularities propagate perpendicular to the Earth’s magnetic field at the ion acoustic velocity [McDonald et al., 1974]. Type II irregularities are generated by the gradient drift instability and are found to propagate smaller than the ion-acoustic speed [Rastogi, 1972]. Type II irregularity also known as cross field or $E \times B$ instability because of cross $E$ and $B$ form the driving forces. These irregularities are practically always present both during the day and the night, even when type I irregularities are absent since, Type II irregularities emerge when the electron drift is insufficient to produce type I irregularities [Rastogi, 1972; Bhattacharya, 1991].

During the daytime the large conductivity of the E-region prevents the growth of equatorial F-region of plasma instabilities by short-circuiting any perturbation electric field associated with plasma wave [Bhattacharya, 1991], however, soon after sunset, these F-region irregularities become visible.

**F-region irregularities:** The other type of irregularities that have been of great scientific interest are the F-region irregularities. Plasma bubbles or plumes are the terms used to describe the F-region irregularities and were initially reported in 1950’s [Booker, 1958]. Since then a number of techniques have been used to study these irregularities, such as the topside and bottom-side ionosonde, radio-star scintillations, VHF-backscatter radar, Langmuir probes on board satellites and the GPS scintillations.

The F-region irregularities are associated with equatorial spread-F (ESF) and can be expected at all latitudes. Spread-F generally remains confined around the geomagnetic equator which is $20^\circ$ on either side of the dip equator. Instabilities can occur in the post-sunset hours at the equatorial latitude of the F-region of the ionosphere [Fejer et al., 1999; Bhattacharya et al., 2006]. It is now accepted that the ESF occurs at the bottom of the F-region due to the Gravitational Rayleigh-Taylor (GRT) instability. Dungey in 1956 [cited in Makela and Otsuka, 2011] originally proposed the idea of
GRT as the physical mechanism for the growth of equatorial plasma bubbles (EPBs). The condition for GRT develops after sunset at the geomagnetic equator when the bottom-side of the F-layer recombines with the dense neutral atmosphere [Beer, 1974]. Simultaneously, the pre-reversal enhancement raises the F-region to higher altitude. As a result a sharp vertical gradient in electron density exists. This condition of high density plasma on top of low density plasma is very unstable [Guzdar et al., 1981]. Using the analogy of fluid dynamics, it could be modeled by having a less dense fluid supporting a high density fluid, on top, against the gravity. In here, it is the high density F-region (representing the heavy fluid) supported on the lesser dense one by the magnetic field [Guzdar et al., 1981]. As this equilibrium is disturbed, the gravitational energy stored in the higher F-region is liberated and the F-layer plunges in. Consequently, a lump of the low density layer rises causing density irregularities known as equatorial plasma bubbles (EPBs) [Singh et al., 1997; DasGupta et al., 2006]. The growth rate of the GRT instability depends on the density gradient. The gradient becomes steeper after sunset. The EPBs are generated after sunset at the magnetic equator. Due to GRT instability, the EPBs rise to higher altitudes and then travel to higher latitudes due to non-linear evolution of the $E \times B$ drift [Guzdar et al., 1981; Fejer et al., 1999; Unnikrishnan and Ravindran, 2010].

Parameters like background electron density gradients, electric fields, zonal winds and vertical winds play a very important role in the growth of GRT instability [Chen et al., 1983]. When fully grown these irregularities contain a wide range of scale sizes which have been detected by ground based radio sounders, night airglow measurements, satellite measurements and backscatter radar echoes. Studies have shown that ESF occurs more often in the equatorial region [Beer, 1974; Davies, 1980; Singh et al., 1997; Sastri, 1998; Basu, 2002] which appears to be closely related to the increase in the height of the F-layer at the low latitudes [Fejer et al., 1999; Beaujardiere et al., 2004].

Ionospheric irregularities have also been classified into different categories according to their scale sizes; Planetary (> 1000 km), Medium Scale (10-100 km), Intermediate Scale (0.1-10km), Transitional Scale (10-100 m), and the Short Wavelength Scale (< 10 m) [Livingston et al., 1981]. The tendency of these
irregularities to interfere with trans-ionospheric communication is quite high. Plasma irregularities cause rapid fluctuations known as scintillations in phase and hence amplitude of signals passing through the ionosphere. Daytime random scintillations occur due to Sporadic E-layer and the night-time predominantly due to the ESF in the low and equatorial latitudes.

1.3 Geomagnetic Storms

The geomagnetic storm or simply magnetic storm is characterized by a depression in the horizontal component ($H$) of the Earth’s magnetic field usually lasting over several hours to days [Gonzalez et al., 1994]. The depression in the Earth’s magnetic field is produced by enhanced solar wind-magnetosphere coupling through the magnetic reconnection mechanism [Dungey, 1961] and the strength of storm at low latitudes is measured by ring current $Dst$ index [Gonzalez et al., 1994].

Geomagnetic storms can affect technological systems like electricity distribution grids by inducing Geomagnetically Induced Currents (GICs) and satellites in a variety of ways by inducing drag, damaging the solar cells and damaging electronic components on board [Kumar and Gwal, 2000; Jain et al., 2010]. The geomagnetic storms, apart from affecting the ground based and space based technological systems at high latitudes, can also affect the F-region ionosphere at low and equatorial latitudes. The Total Electron Content and scintillations responds in a unique manner to each storms and further discussion on this subject has been done in Chapter 5.

During the storm, the ionospheric electric field, neutral wind, and neutral composition have often been observed to deviate from their quiet time patterns [Buosanto, 1999]. These storm-generated disturbances can extensively affect the low-latitude ionosphere. During the geomagnetic storms, the zonal electric fields generated either enhances or reduces the daytime eastward electric field which results in a stronger or a weaker plasma fountain, respectively. Normally, the storm-generated electric fields are short lived prompt penetration electric field originating from the solar wind-magnetospheric dynamo and a longer time-lasting disturbance dynamo electric field [Sastri, 1988]. The penetration electric field is found to be eastward in daytime and westward at night, having the same polarity as the quiet time zonal electric field and has
a time scale of less than 2 h depending on the magnetospheric conditions present for the shielding electric field to build up [Sastri et al., 1997; Araujo-Pradere et al., 2006]. On the other hand, the disturbance dynamo electric field has an opposite polarity to the quiet time zonal electric field and often occurs several hours after the storm onset, lasting from several hours to more than a day [Sastri, 1988]. Due to these electric fields the main phase of the storm results either in a positive ionospheric storm (increase in VTEC) or a negative ionospheric storm (decrease in VTEC). Disturbances in the neutral composition of plasma also modifies the [O]/[N2] global distribution ratio that can further affect the production and loss of plasma producing a positive or negative storm effect [Fuller-Rowell et al., 2002].

The total duration of the magnetic storm is classified in four phases; storm sudden commencement (SSC), initial phase, main phase and the recovery phase, each with characteristic features. Geomagnetic storms have been classified into two categories; (i) Storm sudden commencement (SSC) type and (ii) Storm gradual commencement (SGC) type.

**Storm sudden commencement (SSC):** As the high energy solar wind comes in contact with the magnetosphere, the compression of the geomagnetic field at the boundary of the magnetosphere increases. This increase in wind brings about a sudden increase of the magnetic field at the surface of the Earth and is called the sudden impulse or SSC [Webb et al., 2001] which is the first phase. The abrupt solar wind has the form of a shock wave and is followed by steady enhanced solar wind resulting in a continuing compression of the Earth’s magnetic field. This compression leads to an increase in the magnetic field at the surface of the Earth and is known as the initial phase of the storm. This usually happens after a few hours of the SSC [Ratcliffe, 1972].

After the enhanced solar wind has reached the magnetopause, there is an increase in the number of energetic particles in the magnetospheric trapping region or the outer radiation belt. As the number of energetic particles (electrons and protons) in the trapped trajectories increases, the electrons and protons drift in opposite directions due to being oppositely charged, the ring current around the Earth is produced. Since the direction of this current is westward, it decreases the surface magnetic field or the
H-component of the Earth’s magnetic field which is referred to as the main phase of the storm. The main phase could last from a few hours to 1-2 Days [Ratcliffe, 1972].

The final stage is the recovery phase of the storm whereby the field returns smoothly to normal with an exponential time constant [Ratcliffe, 1972]. The recovery phase is typically about one day but sometimes much longer: the initial recovery is often faster than later one. Recovery results from a decrease in the ring current plasma when the source is terminated and the existing plasma is lost by various mechanisms [Knecht and Shuman, 1985]. Table 1.1 gives a summary of each phases.

<table>
<thead>
<tr>
<th>Storm Phases</th>
<th>Effects</th>
<th>Approximate Time</th>
<th>Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSC</td>
<td>Impulsive increase of field</td>
<td>~ 1 min</td>
<td>Impact of plasma “front” on boundary of magnetosphere</td>
</tr>
<tr>
<td>Initial Phase</td>
<td>Field increased</td>
<td>2-6 Hours</td>
<td>Compression of field by impinging plasma</td>
</tr>
<tr>
<td>Main Phase</td>
<td>Field depresed- Strong daily variations are superimposed on this storm time behavior</td>
<td>1-2 Days</td>
<td>Orbiting charged particles in magnetosphere give ring current</td>
</tr>
<tr>
<td>Recovery Phase</td>
<td>Field returns exponentially to normal</td>
<td>1 Day</td>
<td>Particles removed by collisions (charge exchange) with neutral atom</td>
</tr>
</tbody>
</table>

**Storm gradual commencement (SGC):** Storms of this type show no clear indication of the onset and thus they initiate gradually and are identified by the main phase only. Hence, the two phases of this type of storms are the main phase and the recovery phase. These storms are characterized by two types of fields; the field caused by the compression of the magnetosphere and the field produced by the ring current [Eranna et al., 2007].

The occurrence rate of magnetic storms depends on the solar activity. The Sun shows a 27 day periodic cycle and 11 year solar cycle. The solar activity is monitored using two indices: sunspot numbers and 10.7 cm radio solar flux.

**Sunspot Numbers (SSN):** The sunspots are regions of intense magnetic fields. Initially, the sunspot number index was often called Wolf number with reference to the Swiss astronomer J. R. Wolf who introduced this index in 1848. It is also known as the Zurich
Sunspot Number, since for many years, solar sunspot numbers were derived at the Zurich Observatory, Switzerland [Hanslmeier, 2004]. The sunspots on the Sun emerge and diminish over an 11-year solar cycle. Over this cycle, solar maximum is the period of maximum sunspot number or most energetic interval and solar minimum is the period of least sunspot activity. At solar minimum, many days can go without any visible spots. At maximum, there may be several hundred sunspots on any day. This cycle has persisted for centuries. The sunspots change continuously. At solar maximum, the number of eruptive events (like solar flares) and geomagnetic activity (or geomagnetic storms) are at their peak occurrences.

**10.7 cm or 2800 MHz Solar Radio Flux:** This was initially recorded in Ottawa, Canada, by radio telescopes from 1947 to 1961. From 1961 up till 1991 it was recorded by Algonquin Radio Observatory in Ontario, Canada. Then from 1991 to present it is recorded at the Dominion Astrophysical Observatory, British Columbia. The sun emits radio flux which changes from day to day in response to the number of sunspot groups on the disk. Solar flux from the entire disk has been routinely recorded at a frequency of 2800 MHz since this frequency, being in the UV band has been found to produce photoionization in the Earth’s ionosphere. The observed values are adjusted for the changing Sun-Earth distance and for uncertainties in antenna gain. From this index, the 27 day solar rotation periods can easily be identified [National Research Council Canada, 2009].

Geomagnetic activity does not follow the trend, but instead trails the sunspot peak. So, as the solar activity approaches its peak, the frequency of the geomagnetic storms also increases [Webb et al., 2001]. The strength of magnetic storms at low latitudes is measured by ring current \( D_{st} \) index.

**\( D_{st} \) index:** It stands for Disturbance Storm Time and is derived from a network of near-equatorial geomagnetic observatories that measure the intensity of the globally symmetrical equatorial electro-jet or the ring current. Thus, \( D_{st} \) monitors the variations of the globally symmetrical ring current, which encircles the Earth close to the magnetic equator in the Van Allen (or radiation) belt of the magnetosphere between 2-7 Earth radii [McPherron and O'Brien, 2001]. The \( D_{st} \) index was first introduced by Sugiura and Chapman in 1960 after a comprehensive analysis of storm morphology at 26 middle
and low latitude stations [Gonzalez et al., 1994]. Dst is hourly average values of the global variation of the low latitude H component of surface magnetic field. H and Z are the components of the Earth’s magnetic field at ground based observatories whereby: H – is the horizontal component, Z – is the vertical component and another measure D – is the dip angle between the field vector and H component. This Dst values for research are obtained from the World Data Center (WDC) for Geomagnetism, Kyoto University, Japan website http://wdc.kugi.kyoto-u.ac.jp/dst_realtime/presentmonth/index.html.

1.4 GPS based Total Electron Content (TEC)

As the high frequency radio wave traverse through the ionosphere, they undergo a series of transformation before emerging on the other side. This includes [Klobuchar, 1985]:

- Group delay or retardation
- RF carrier phase advance
- Doppler shift of the RF carrier of the radio wave
- Faraday rotation of the plane of polarization of linearly polarized waves
- Angular refraction or bending of the radio waves
- Distortion of the waveform of transmitted pulses
- Amplitude and phase scintillations

All the effects listed above, except for amplitude and phase scintillations (see section 1.5 for details), are proportional to the total number of electrons encountered by the radio wave as it passes through the ionosphere. As a result, three direct methods of measuring the total electron content (TEC) of the ionosphere using radio wave techniques have been developed. These are: 1) Faraday rotation, 2) Group delay, 3) Differential carrier phase. Subsequently, the Faraday rotation technique was extensively used to measure TEC until the development of Navy Navigational Satellite System (NNSS) and later the Application Technology Satellite-6 (ATS-6) [Davies, 1980]. The ground based techniques like ionosonde and HF radar are also used to investigate the ionosphere up to F-region conventionally. The most important effect studied using the satellites, is the group delay on the modulation [Klobuchar, 1989]. Recently, the
operation of NAVSTAR GPS (Navigational Satellite Timing and Ranging Global Positioning System), provided an opportunity for researchers to measure the differential phase or group delay using a dual frequency GPS receiver and this method has been used in this research. The technical details of the GPS system are as follows:

The GPS is a satellite based radio navigation system that provides accurate information about position, velocity of moving receiver, and time continuously under all weather conditions around the globe. The whole system is owned and operated by the US Department of Defense (DoD) and was developed mainly for US military applications, however, it is now used widely in civilian communities in most countries with a wide range of applications. The GPS system can be divided into the three segments:

i) **The Space Segment:** There are 31 satellites located in six circular orbits at approximately 20,200 km altitude of which at least 24 satellites are available at any instance. The six orbits are inclined at 55° up from the geographic equator and are spaced 60° apart. The orbital period is 11 hours and 58 minutes which is about half a sidereal day, meaning that each satellite completes about two full revolutions each day [French, 1996]. Each satellite weighs approximately 2000 pounds and is 17 feet across with the solar panels extended. The width including wing span is 38.025 feet. Rocket boosters are also placed to control the satellites path.

ii) **The Control Segment:** The motion and positions of satellites are controlled and corrected by 5 base stations located around the globe that includes: Ascension Island (Atlantic Ocean), Diego Garcia (Indian Ocean), Hawaii and Kwajalein (both in Pacific Ocean). The single master control station in operation is located at Schreiber Air Force Base in the State of Colorado, USA. In the event of some catastrophic failure, there are two backup Master Control Stations, one located in Sunnyvale, California, and in Rockville, Maryland. The function of the Control Segment is to ensure that the Space Segment is operating within specifications and to provide adjustments where necessary. Control Segment and the GPS satellites communicate via an S-band uplink from one of the four ground station antennas.
iii) **The User Segment:** User segment consists of five modules namely antennas, receiver, signal processing and data processing capabilities input/output device such as a control display unit and a power supply. The GPS is distance (ranging) system, whereby, the user’s location is calculated in relation to any given satellite. Ground receivers passively receive the radio signals from each visible satellite and measure the time it takes the signal to travel to the receiver. Distance is then computed by formula \( D = C \times t \), where \( C \) is the velocity of EM wave in free space \((3 \times 10^8 \text{ ms}^{-1})\). Figure 1.4 shows all the three segments of the GPS system.

The satellites transmit two radio signals. These signals consist of a C/A (coarse acquisition) code at 1.023 MHz and a P (precision) code at 10.23 MHz bandwidths, respectively. The signals are transmitted at two carrier frequencies \( L_1 = 1575.42 \text{ MHz} \) (wavelength = 19.04 cm) and \( L_2 = 1227.60 \text{ MHz} \) (wavelength = 24.44 cm). Every GPS users can access the C/A code, whereas the P-code is only accessible to authorized users.

The signals transmitted by satellites are controlled by atomic clock within an accuracy of 20-30 ns. The carrier signals \( L_1 \) and \( L_2 \) are biphasic modulated by codes to provide satellite clock readings and other information like orbital parameters to the receiver. The codes consist of a sequence or string of binary values of 0 or 1, while, the biphasic modulation is performed by a 180° shift in the carrier phase whenever a change in the code state occurs [Kuzminykh, 2010]. The navigation message is modulated using the two carriers (\( L_1 \) and \( L_2 \)) at a chipping rate of 50 bits per second (bps) which contains information on the satellite’s pseudo-random code/number (PRN), ephemeris data and almanac data. PRN is an unique identity code that identifies which satellite is transmitting information. Ephemeris data gives information about the functioning of the satellite (whether it is working properly or not), current date and time. This is essential in determining the position. The almanac data notifies the receiver where each GPS satellite should be at any time throughout the day and each satellite transmits almanac data showing the orbital information for that satellite and every other satellite in the system [Kuzminykh, 2010].
GPS offers two levels of navigation and positioning; Standard Positioning Service (SPS) and Precise Positioning Service (PPS). The SPS gives 100 m horizontal accuracy, 156 m vertical accuracy and 167 ns time accuracy. With PPS the accuracy increases to 17.8 m horizontal accuracy, 27.7 m vertical accuracy and 100 ns time accuracy [French, 1996].

Recently, civilian uses of GPS have far out paced the US DoD’s purpose of implementing it. GPS is being used in land, sea, air and space navigation, search and rescue missions, surveying recreation as well as in Intelligent Vehicle Highway Systems (IVHS). A modification to the receiver with Kalman Filter, the dual frequency GPS receivers has been used to record the ionospheric parameters like TEC and scintillations.

![Diagram of GPS System](image)

**Figure 1.4**: The operation of GPS system. Reproduced from Kuzminykh [2010].

The major limiting factor in accuracy of GPS is the ionospheric refraction. The GPS uses an ionospheric correction model to account for this refraction. However, due to the dynamic nature of the ionosphere, this model does not compensate for all the parameters and as a result, the ionospheric refraction influxes an error of up to 30 m in
space coordinates [French, 1996] due to a delay in the code information. The group delay in the GPS code, as discussed previously, is due to the TEC along the signal path. The TEC is given by

\[
\text{TEC} = \frac{\text{Satellite}}{\text{Receiver}} N \, ds
\]  \tag{1.0}

where: \( N \) is the electron density, measured in TEC units. 1 TEC unit = \( 1 \times 10^{16} \) electrons/m\(^2\).

The additional time delay (\( \Delta t \)) of a signal transmitted from above the ionosphere to a receiver either on or near the Earth’s surface is given by

\[
\Delta t = \frac{q}{2c\varepsilon m_e f^2 (2\pi)^2} \rho n_e d\rho
\]  \tag{1.1}

where: \( c \) is the velocity of light in free space,
\( \varepsilon \) is the permittivity of the medium,
\( m_e \) is the mass of the electron,
\( f \) is the frequency of transmitted/received signals in hertz and
\( n_e \) is the number of electrons.

When reduced equation 1.1 can be written as [Klobuchar, 1985]:

\[
\Delta t = \frac{40.3}{cf^2} \times \text{TEC}
\]  \tag{1.2}

A dual frequency receiver measures the difference in time delay between the two \( f_1 \) and \( f_2 \) frequencies given by

\[
\Delta t = \frac{40.3}{c} \times \frac{\text{TEC}}{f_2^2 - f_1^2}
\]  \tag{1.3}

The US DoD started measuring the ionospheric group path delay in early 1980s, on the two carrier frequencies L1 (1575.45 MHz) and L2 (1227.60 MHz), in order to correct the ionospheric time delay for better accuracy. The two frequencies transmitted by the GPS system are the 154\(^{th}\) and 120\(^{th}\) harmonics of 10.23 MHz. This 10.23 MHz is bi-phase modulated on both carriers with a pseudorandom code resulting in a \( [(\sin x)/x]^2 \) shaped spectrum with 20 MHz width to the first nulls [Klobuchar, 1989]. The 10 MHz modulation is transmitted with a known phase difference, therefore, the difference in
phase of the received signal is a direct measure of ionospheric group path delay. The TEC was found to be proportional to the Ionospheric differential delay ($I_\rho$) between L1 and L2 signals given as

$$I_\rho = -I_\varphi = \frac{40.3 \times \text{TEC}}{f^2}$$

(1.4)

The $I_\rho$ is measured in terms of pseudorange and $I_\varphi$ is the ionospheric delay term in measurements of carrier phase.

It has been found that at night the ionospheric delay is approximately five to ten times less than that at daytime [Komjathy, 1997]. The diurnal cycle for TEC is such that the maximum occurs two hours after solar noon, and a minimum occurs before dawn. The highest TEC values do not occur at the equator, rather in the equatorial anomaly region. Figure 1.3 shows anomaly region with a width of about 10° which can extend up to 30° on either side of the geomagnetic equator. Our GPS system is located in Physics building of the University of the South Pacific, Suva, Fiji Islands (lat: 18.15° S, geomag lat: 21.07° S) lies in the anomaly region as shown in Figure 1.3 and provides an inimitable site to study the TEC variation and scintillation occurrence.

### 1.5 GPS L-Band Scintillation

As the radio wave traverses through the ionosphere the amplitude and phase suffer distortion when the signal encounters the ionospheric irregularities. This fluctuation in the radio wave is called scintillation and is similar to twinkling of stars due to non-homogenous nature of the troposphere. Scintillation occurs when the depleted ionospheric plasma (plasma bubble) also known as irregularities come into the line-of-sight between the satellite and receiver [Aarons and Basu, 1985; Bhattacharyya et al., 2006]. These irregularities develop phase fluctuations across the wavefront. When the wave emerges out of the irregularity and propagates towards the ground receiver, phase mixing or interference occurs, as a result, both phase and amplitude fluctuations are observed.

The ionosphere produces significant scintillations on the L1 signal transmitted from GPS satellites and may degrade the GPS performance [Thomas et al., 2001]. Scintillations can infuse GPS ranging error and if very strong scintillation events crop
up then the receiver can experience loss-of-lock as shown in Figure 1.5. Hanslmeier [2004] suggested that the stronger the scintillation the greater is the impact on the communication and navigation systems.

The scintillation measurements have been used as a fundamental tool in analysis of ionospheric irregularities. Scintillation data is imperative in determining the spatial and temporal distribution of ionospheric irregularities as well as in studying the physical processes which lead to the formation of irregularities. In addition, scintillation characteristics can also be used to study the performance and the level of degradation of the radar system and the trans-ionospheric communication links [Basu and Basu, 1989].

![Figure 1.5: Ionospheric effects on GPS signals; a) Ranging Error, b) Scintillations. Reproduced from [Kitner, 2008].](image)

The occurrence of scintillations depends upon local time, season, solar cycle, latitude, longitude and geomagnetic activity, but the day-to-day randomness in the occurrence of scintillations makes their predictions still a challenging problem [Van-Dierendonck and Rastburg, 2005]. The low latitude scintillation activity is basically a nighttime phenomenon with high occurrence during high solar activity [Basu and Basu, 1989]. It is lucid that during high solar activity period, scintillations are intense with higher occurrence in auroral and equatorial regions. In mid-latitude region, scintillation is a rare phenomenon and occurs only in cases of extreme levels of ionospheric storms.
[Datta-Barua et al., 2003]. During these ionospheric storms, the active aurora expands both pole-ward and equator-ward, exposing the mid-latitude region to scintillation activity.

Early study by Crane [1974] has shown that a strong correlation exists between scintillation occurrence and the formation of spread-F irregularities. However, the study indicated a very weak correlation of scintillations with sporadic-E and spread-E type irregularities. This implies that most of the scintillation occurrence is due to F-region irregularities which are found to be at altitudes between 250 and 650 km. Basu and Basu [1989] found maximum occurrence of amplitude scintillations in the equatorial region. The equatorial scintillations are produced by equatorial plasma density depletions or bubbles caused by the Gravitational Rayleigh-Taylor (GRT) instabilities. GRT instabilities occur after sunset (Formation of GRT is discussed in the section 1.2) at the base of F-region and rise to higher altitudes due to non-linear evolution of $E \times B$ drift.

The two areas of the globe as shown in Figure 1.6, troubled by the L-band scintillations are: i) ± 20° wide belt of latitude around the geomagnetic equator also referred as low latitude or the tropical zone, and ii) The region lying between sub-auroral to polar latitudes.

Figure 1.6: The global distribution of scintillation occurrence during a) solar maximum and b) solar minimum. [Basu and Basu, 1989].
In this study amplitude scintillation measurements and analysis have been carried out for all the days of 2010 and phase scintillation analysis has only been done in instances of strong amplitude scintillation events. The intensity of the scintillation is characterized by a number of amplitude scintillation indices; \(S_1\), \(S_2\), \(S_3\), and \(S_4\) which are defined as follows [Bartusek and Felgate, 1966; Fremouw and Bates, 1971]:

\[
S_1 = \frac{<SI> - <SI^2>}{<SI>^2} \tag{1.4}
\]

\[
S_2 = \frac{<(SI - <SI>)^2>}{<SI>} \tag{1.5}
\]

\[
S_3 = \frac{<SI^2 - <SI>^2>}{<SI understood> \tag{1.6}
\]

\[
S_4 = \frac{<SI^2> - <SI>^2}{<SI}> \tag{1.7}
\]

where: \(SI\) and \(SI^2\) are the signal intensity and power respectively and, \(< >\) represents the time averages.

The \(S_1\) gives the normalized deviation of amplitude and \(S_2\) is the normalized root mean square deviation of signal amplitude. The \(S_3\) is the normalized deviation of signal power and the \(S_4\) gives normalized root mean square deviation of signal power.

Briggs and Parkin [1963] investigated the relationship between these indices empirically for satellite scintillation and showed that \(S_1 = 0.42 S_4\), \(S_2 = 0.52 S_4\), \(S_3 = 0.73 S_4\). The \(S_4\) is the most widely used amplitude scintillation index which is also defined as the ratio of the standard deviation of signal intensity to the average signal intensity [Basu and Basu, 1989]. \(S_4\) is more statistically stabilized with an upper limit of 1 and a lower limit of 0. This gives a better fit to the observed signal power values [Crane, 1974]. Thus, \(S_4\) index has been used in our study to investigate the spatial and temporal variation of L-band scintillation. The \(S_4\) is derived from de-trended signal intensity of received signals from all the visible satellites and is normally computed over 60 s intervals with the GSV 4004B receiver. The scintillation activity was categorized according to the \(S_4\) index values into weak (\(0.2 \leq S_4 < 0.3\)), moderate (\(0.3 \leq S_4 < 0.45\)) and strong (\(0.45 \leq S_4\)) with that \(S_4\) less than 0.1 were discarded since these are due to noise [Ramarao et al., 2006a]. A detailed account of scintillation results will be discussed in Chapter 4.
1.6 Literature Review

After Marconi’s trans-Atlantic demonstration of wireless communication technique in 1889, numerous people were inspired to determine the ultimate capabilities of this newly discovered resource, the ionosphere. Initially it was called Kennelly-Heaviside layer since this layer reflects electromagnetic waves. Later, the scientific findings of Appleton and Barnett [1925] and by Breit and Tuve [1925 & 1926] confirmed the existence of this reflecting layer which was named the ionosphere. The invention of ionosonde in 1925 led to the sounding of the ionosphere. By 1947, ionosondes were routinely used to measure the characteristics of the ionosphere. During 1957-58 an international worldwide network of ionosondes was established to study the spatial variations of ionosphere [Hays et al., 1988].

Afterwards various methods including VHF, UHF, MF and Incoherent Scatter Radars and Optical Airglow Emission methods have been used to study the ionosphere. Equipment like Langmuir Probes, Retarding Potential Analyzer and Drift Meters were developed on different platforms like on the ground, in air balloons, onboard rockets and satellites, to study ionosphere [Hays et al., 1988]. Satellites such as; Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) and Communications/Navigaton Outage Forecasting System (C/NOFS) have advanced sensors onboard to study the features of ionosphere [TIMED SDS Manager, 2011].

Total electron content (TEC) and the L-band scintillations are two most important parameters to study the morphology of the ionosphere. Substantial amount of work has been carried out on TEC and scintillations around the globe, however, not much has been done in the South Pacific region.

1.6.1 Total electron content (TEC)

The ionospheric total electron content (TEC) is one of the most important descriptive physical quantities of the ionosphere. TEC has been widely studied and modeled for scientific research and also for other applications like satellite navigation, error correction to operational systems, determining the scintillations on radio wave and satellite altimetry [Ercha et al., 2012]. The literature on TEC studies is large so we
would like to concentrate only on studies closely related to trans-ionospheric methods. The studies on ionosphere commenced in 1950’s after the development of ionosonde. The trans-ionospheric techniques emerged during that time were the Differential Doppler and Faraday Rotation of lunar reflected VHF waves [Klobuchar and Mendillo, 1973; Davies, 1980].

In 1957, the successful launch of artificial satellite Sputnik I provided the first opportunity to study the ionosphere [Davies, 1980]. Since, then ionospheric researchers turned to study the trans-ionospheric waves from artificial satellites using various methods. In 1960s, the Application Technology Satellite 3 (ATS-3) satellite was used for ionospheric studies and later in 1966 a geosynchronous satellite ATS-6 was conceived as the first radio beacon designed specifically for ionospheric studies [Hargreaves, 1978]. Since then a number of satellites have been launched and used for TEC studies including; Beacon Explorer-B (BE-B also known as: S-66), Engineering Test Satellite-2 (ETS-2 also known as: Kiku-2), Satellite Italiano per la Ricerca Industriale Operativa (SIRIO) and Atmospheric Explorer-E (AE-E) [Klobuchar et al., 1973]. Bougeret [1981] used two correlation interferometers to detect gravity and acoustic waves in the F2-region at Meudon (long: 47.4° N, lat: 2.2° E), France, and found that the perturbations are maximum around mid-day and occur more frequently in winter during 1979, a high solar activity period. Sukumar [1987] did a comparison of differential phase path corrections using the Slab model and the Bent model using the Ooty Synthesis Radio Telescope (OSRT) operating on 326.5 MHz at Ootacamund (11° N), India. He found that the Slab model overestimates the corrections by 40% in comparison with Bent Model and deviations are more pronounced in the regions close to the equator.

The proposal of satellite geodesy was dated back to April 1955 as the scientists at the Naval Research Lab (NRL) proposed a scientific satellite for the field of geodesy, which became fully operational in 1995 with GPS [Evans et al., 2002]. In the transitional phase of GPS, with the launch of first, Block I satellite in 1978, the researchers discovered the method of differential group delay technique, which was widely used afterwards [Klobuchar, 1989]. According to Coco [1991] the first large scale scientific research on the ionosphere using GPS took place in 1981 with the data
collection at Ascension Island, in the Atlantic Ocean near the equator. This campaign was a joint effort between the Air Force Geophysics Lab (AFGL) and Stanford Geophysics Research Lab. After 1986 AFGL and Applied Research Laboratory; University of Texas (ARL:UT) started participating in a series of campaign to measure TEC. During 1991 two geostationary satellites (GOES II and GOES III) were used for ionospheric monitoring over the whole continent of United States [Coco, 1991]. Mercier and Jacobson [1997] did a study on verifying the radio interferometry technique used in observing the atmospheric gravity waves at Los Alamos (35.87° N), USA, using three years data (January 1993 – May 1996) from four geostationary satellites; ATS-1, ATS-3, GOES II and GOES III. They found that this method was appropriate and consistent, however, the main limitation was the poor coverage in lines of sight, due to small number of visible satellites.

At present the full operation of GPS satellites differential group delay technique is widely used by researchers around the globe for TEC studies. Mannucci et al. [1993] discussed the process of monitoring ionosphere using the GPS and suggested that through GPS monitoring a better ionospheric mapping could be achieved. Wanninger [1993] did a study on GPS TEC at Kokee (20° N), Hawaii, during 1992, and found that GPS dual frequency receiver could be used to investigate the ionosphere though it was not designed for ionospheric research and can contribute to the global mapping of the TEC as well as provide TEC models for the corrections.

Komjathy and Langley [1996] studied the effect of cut-off angle and shell height bias on GPS TEC at a number of mid and high latitude stations. They found that cut-off angle induces a bias of 0.3 TECU with standard deviation (SD) of 0.5 TECU and shell height induces a bias of 2 TECU only. On the other hand, Davies and Hartman [1997] did a comparison of ionospheric TEC using GPS and GOES II satellites data during 1994 and 1995 at Boulder (40° N), Colorado. They used Faraday rotation of 136 MHz signal from GOES II satellite to obtain TEC and compared that with GPS TEC and found that diurnal variations were in overall agreement, however, the nighttime GPS TEC was higher when compared to TEC obtained using GOES II satellite data. They finally concluded that with proper attention to receiver citing and calibration, the absolute values of GPS TEC should be within 3 TECU. Komjathy [1997] studied the
global ionospheric TEC using GPS and demonstrated that the University of New Brunswick’s (UNB) algorithm was capable of modeling the diurnal variation of TEC even during the geomagnetic storm periods. He also modified the International Reference Ionosphere 1995 (IRI-95) model to update its coefficient sets using the UNB’s GPS-derived regional ionospheric maps, based on a 5 week long GPS campaign. With that Ciraolo and Spalla [1998] compared the TEC measurements using GPS and NNSS (Navy Navigation Satellite System) during 1994, 1995 and 1996 at Matera (40.5° N), Italy, a mid latitude station. They found that during 1994 the median was 2.59 TECU, lower quartile (LQ) was 1.11 TECU and upper quartile (UQ) was 4.02 TECU. During 1995 the median was 2.38 TECU, while the LQ was 0.97 TECU and UQ was 3.58 TECU. The 1996 results showed a median of 1.49 TECU, with a LQ of 1.63 TECU and UQ of 3.11 TECU. Another comparisonal study was done by Warrant and Jodogne [1998] at Belgium using the data recorded during 1995 and 1996, who compared ionosonde measurements and the GPS TEC using Turbo Rogue GPS receiver. They found that TEC using GPS and ionosonde was in good agreement. Davis [2000] did a comparison between GPS TEC and TEC from low airglow and aurora spectrograph (LORAAS) sensor aboard the Advanced Research and Global Observing Satellite (ARGOS) recorded at Colorado (39.05° N) during 1999 and found that if the corrections are removed then the values correlate well with IRI-95 and GIM TEC. Jakowski et al. [2002] studied the GPS and GLONASS based TEC variations at Ispra (45.8° N), Italy, Porz (50.87° N) and Neustrelitz (53.4° N), Germany, in the European region during 2000 and found that GPS and GLONASS measurements can effectively be used to estimate the horizontal distribution of TEC on regional and global scales. Garner et al. [2008] studied the TEC using the GPS (transmitting at L-band) and low Earth orbiting (LEO) spacecrafts OSCAR-23, OSCAR-25 and FORMOSAT (transmitting at 150 MHz and 400 MHz) recorded at Oneonta (42.45° N), New York, during 2006. They found that these methods give a better match of TEC measurements than the IRI-2000 model since IRI-2000 only estimates the TEC up to 2000 km while satellites have access to higher altitudes.

The contribution of plasmaspheric TEC to GPS TEC has also been instigated by Bishop et al. [2009] at mid latitude stations in North America. They found that
plasmaspheric contribution to GPS TEC was only 2 TEC units. Since, the above studies reveal that GPS derived TEC compares very well with the ionospheric TEC and the plasmaspheric TEC has very little contribution, researchers began to study the ionospheric TEC using GPS method.

Wu et al. [1997] studied TEC over Taiwan using 9 observational sites covering the latitudes between 21.9° – 26.2° N and the longitudes between 118.4° – 121.6° E, in the Equatorial Ionization Anomaly (EIA) region from September 1996 to August 1997. They found a major diurnal peak at around 15:00 LT and a minor peak around 18:30 LT. The seasonal maximum of TEC occurred in spring (April) and autumn (October) and minimum in winter (January) and summer (July). They also found that EIA crest appears earlier in winter than in summer. Gupta and Singh [2000] studied TEC at Dehli (28.63° N), India, for the period of 1975-1980 and 1986-1989 and found a diurnal maxima at 14:00 LT and specifically, in winter and equinox, a post sunset secondary maximum around 20:00 LT. The diurnal peak in equinoctial months is greater than that in the summer and winter months. Kumar and Singh [2009] studied the variation of TEC at Varanasi (25.28° N), in Indian EIA, during May 2007 to April 2008, a solar minimum period. They found peak VTEC at around 13.46 LT and maximum TEC values during the equinoctial months and minimum TEC during summer. Bagiya et al. [2009] studied TEC variations at Rajkot (22.29° N), India, during April 2005 to December 2007 and found that diurnal maximum occurred between 14:00 and 16:00 LT. They also found that maximum TEC occurred during equinox (March, April, September and October) and minimum in winter (November, December, January, February) and intermediate in summer. Chauhan and Singh [2010] studied morphological features of GPS-TEC recorded at Agra (27.17° N), India, a low latitude station, during January to December, 2007 and found the diurnal peak between 12:00 and 14:00 LT and a minimum in TEC between 05:00 – 06:00 LT. Galav et al. [2010] did an extensive TEC study at Udaipur (24.6° N) a low latitude in the Indian region during the low solar activity period, January 2005 to January 2010. They found that peak values of TEC occurred between 14:00 and 16:00 LT (Indian standard time), mostly around 14:00 LT in all seasons. Seasonal maximum TEC occurred during equinox and minimum during solstice. They also compared seasonal values of TEC
with the values of TEC obtained using IRI-2007 and found that both were in good agreement. Their study on nighttime seasonal variation of TEC using the annual plot of TEC from 21:00 to 06:00 LT showed higher values during March equinox to September when compared to winter months. Recently, Chauhan et al. [2011] studied variation of GPS-TEC at a low latitude station Agra (27.12° N), India, located just outside the equatorial anomaly crest during August 2006 to July 2009 and found a minimum TEC at 05:00 LT and a maximum at 14:00 LT. They observed the lowest TEC in winter while highest in equinox and summer months. All these studies on low latitude TEC showed a diurnal peak between 14:00 - 16:00 LT and a minima in the morning between 05:00 - 06:00 LT with maximum TEC values in equinox, moderate in summer and minimum in winter. There are no TEC studies in the South Pacific region and not much work has been done on TEC in the southern hemisphere.

The spatial variation of TEC has been also analyzed by researchers. Wu et al. [1997] studied the latitudinal variation of TEC from 9 sites distributed over Taiwan between 21.9° N to 26.2° N covering the geographical latitude of 16° - 30° N, during September 1996 and August 1997, a low solar activity period. They found that the mean latitude and local time for the daily EIA crest are 20.4° N and 14:30 LT. Mendillo et al. [2000] studied the TEC over the South American stations; Bogota (4.5° N)-Colombia, Arequipa (16° S)-Peru and Santiago (33.4° S)-Chile during 1996 and 1998. Arequipa is located near the magnetic equator while Bogota is in the Northern anomaly and Santiago in the Southern anomaly. They found that the EIA appears during afternoon hours, extending until post-midnight and disappears in the predawn hours. Their results also demonstrated that the EIA peaks are not symmetrical about the geomagnetic equator. The Northern anomaly has greater peak than the Southern during winter. Using two years data of 1998 and 1999, Thomas et al. [2001] carried out a TEC study using GPS at Marak Parak (6.31° N), Malaysia, Pontianak (0.00°), Indonesia, Vanimo (2.4° S), PNG, Parepare (3.98° S), Indonesia, and Darwin (12.4° S), Australia. With having a mask angle of 15°, they found the coverage circle around each station to be 1140 km, thus this covered a latitude of 35° around geomagnetic equator. They found maximum TEC in the anomaly region rather than at the magnetic equator. Under the GPS Aided Geoaugmented Navigation (GAGAN) project, a network was established to monitor the
TEC at 18 stations distributed all over India covering the geographic latitude of 8° to 32° N in the range of 1° S to 23° N geomagnetic latitude [RamaRao et al., 2006a]. The study under the GAGAN project carried out during low solar activity, period from March 2004 to June 2005 showed a short lived minimum between 05:00 – 06:00 LT in the EIA zone from Trivandrum (8.47° N) to Raipur (21.18° N) whereas beyond the anomaly crest, at Dehli (28.58° N) and Shimla (31.09° N) the minimum was flat during the nighttime hours (22:00 - 06:00 LT). The early morning increase in TEC was fast at EIA stations when compared to mid-latitude stations. At an equatorial station, Trivandrum, the day maximum was broad with longer duration compared to that at the anomaly crest. The maximum diurnal TEC also showed latitudinal variation. At Trivandrum peak occurred between 16:00 and 17:00 LT while, at Kolkata (a sub-tropic station latitude: 22.6° N) peak occurred between 12:00 and 14:00 LT. At other stations peak diurnal TEC occurred between 13:00 – 16:00 LT. Daytime variation of TEC at equator showed a minimum of 5 TEC units and maximum of 50 TEC units. In the Indian EIA region the minimum TEC was 5 TEC units and maximum was 90 TEC units. This correspond to range delay of 8 m at equator and 15 m in EIA as far as GPS ranging error is concerned. Seasonal variation showed maximum TEC in the equinoctial months (September and October) and in the winter month of November. The latitudinal variation revealed that the daytime maximum value of TEC increases from the equator to the anomaly crest region (Raipur: 21.18° N and Bhopal: 23.28° N) and decreases significantly at stations outside the anomaly crest regions (Dehli and Shimla) [RamaRao et al., 2006a]. DasGupta et al. [2007] studied TEC under the GAGAN project covering a latitude of 8° to 32° N in India and found a sharp latitudinal gradient in diurnal peak TEC with maximum around 13:00 - 15:00 LT recorded near Pune (lat: 19.1° N, long: 74.05° E and dip: 24° N). They also compared the TEC values with IRI-95 model and Parameterized Ionospheric Model (PIM) TEC values and found that the IRI-95 model does not follow the trend of the GPS TEC under the different geophysical conditions, while the PIM-1.6 model could be used with some limitations since PIM-1.6 model fits well with measured data in the late night until early morning at around 08:30 LT.

Solar activity variations of TEC is also an interesting field of study. Warnant and Pottiaux [2000] studied TEC at Brussels, Belgium(50.8° N) a high latitude station,
from January 1996 till August 2000 and found that during solar minimum, the daytime maximum TEC varied from 5-15 TECU, while nighttime TEC was in order of 1 TECU. However, at solar maximum the daytime TEC ranges between 20-85 TECU and the nighttime TEC ranges between 1-20 TECU, illustrating that TEC is dependent on the solar activity. Gupta and Singh [2000] studied the TEC at Dehli (28.63° N), India during 1975-1980 and 1986-1989 periods using ionosonde data. They found that as the solar activity increases, the winter diurnal peak overtakes that of summer, giving a rise to the winter anomaly. In equinox, the diurnal peak increases with F_{10.7} cm solar flux, having a correlation of $r = 0.88$ and reaches a saturation value of 140 TECU. In winter, the diurnal peak increases with F_{10.7} to approximately 140 TECU with $r = 0.85$. In summer, the diurnal peak also follows F_{10.7} with $r = 0.86$, however, the saturation is at 100 TECU. Kumar and Singh [2009] studied TEC variation at Varanasi (25.28° N) in Indian EIA during May 2007 to April 2008, a solar minimum period. They found that TEC showed not much correlation with variations in solar indices F_{10.7} ($r = -0.25$) and SSN ($r = -0.09$). Bagiya et al. [2009] studied TEC variation at Rajkot (22.29° N), India, during April 2005 to December 2007 and found a good correlation between F_{10.7} and TEC with $r = 0.99$. Galav et al. [2010] studied the TEC variation with solar flux at Udaipur (24.6° N), a low latitude station in the Indian region during the low solar activity phase from January 2005 to January 2010. The daytime ionospheric TEC was well correlated with the solar flux with a high correlation coefficient of 0.74. Chauhan et al. [2011] studied variation of GPS-TEC at a low latitude station Agra (27.12° N), India, located just outside the equatorial anomaly crest, during August 2006 and July 2009, a low solar activity period. They compared the TEC variations with three solar indices; EUV flux, 10.7 cm solar radio flux (F_{10.7}) and the sunspot numbers (SSN). It was found that these solar indices show high correlation with day maxima in the summer months than in equinoctial months and low correlation in winter months. The value of correlation coefficient ($r$) for EUV was 0.446 (summer), 0.242 (equinox), and 0.231 (winter). The $r$ for F_{10.7} was 0.509 (summer), 0.313 (equinox), and 0.165 (winter). The $r$ for SSN was 0.287 (summer), 0.205 (equinox), and 0.153 (winter). They also found that the correlation of TEC with SSN was low compared to that with F_{10.7} and EUV during all seasons. These studies show that there is good correlation of TEC with
F_{10.7} at the low latitudes, however, more work is needed to be done in order to establish the exact correlation of TEC with solar indices.

The ionospheric TEC has been found to show the effect of geomagnetic activity and geomagnetic storms. The effect of magnetic storms on TEC had been studied at different places around the globe. Wu et al. [1997] studied geomagnetic activity effect on TEC over Taiwan in the EIA region using 9 observational sites between 21.9° – 26.2° N, between September 1996 and August 1997 and found that the TEC does not correlate well with geomagnetic activity though the diurnal peak was well correlated with Dst \( r = 0.72 \), and weakly correlated with \( Kp \) \( r = 0.41 \). Yizengaw and Essex [1999] studied the effect of 22-24 September 1999 intense geomagnetic storm on TEC at four stations, Townsville (19.6° S), Tidbinbilla (35.4° S), Hobart (42.8° S) and Macquarie Island (77.8° S) in Australia. The main phase of the storm occurred in the daytime on 23 September. They found that at a high-latitude station (Macquarie Island) an increase in TEC by 80-130% and at the mid latitude stations (Tidbinbilla and Hobart) the TEC depletion by 50% between 08:00 LT till 14:00 LT during the main phase of the storm. At the low latitude station (Townsville) a double peak enhancement in TEC was recorded with respect to the average Q-days TEC during the main phase of the storm. While in the recovery phase, there was no significant change in the TEC. Bhattyacharya et al. [2002] studied the F-region irregularities and TEC at Ancon (8.95° N) during the 1-2 March 1999 moderate geomagnetic storm (\( Dst = -95 \) nT) with the main phase in the post-midnight period. They found TEC fluctuations in the pre-midnight period (after 22:00 LT) and a decrease in TEC in the post-midnight period (the initial recovery phase). Pandey and Dashora [2006] studied the effects of two geomagnetic storms on TEC at Udaipur (24.58° N) near the Indian EIA crest. The first storm was a very intense storm (\( Dst = -373 \) nT) on 7-11 November 2004, with main phase in the daytime for which they found a decrease in VTEC during its main phase. The VTEC enhancement was recorded in the daytime and the pre-midnight in the recovery phase. The second storm was an intense storm (\( Dst = -247 \) nT) during 13-17 May 2005, with main phase in the daytime. They found that VTEC enhancement occurred during the main phase of this storm. During the recovery phase there was no significant change in VTEC. Dashora and Pandey [2007] studied the effect of 7-11 November 2004 intense
geomagnetic storm ($Dst = -373 \text{ nT}$) on TEC at Udaipur (24.58° N), India, and found that VTEC on November 8 (during the main phase) was lower by 15 TECU when compared to mean VTEC between 10:30 – 13:30 LT and was consistently lower than the mean VTEC between 13:30-16:30 LT. They attributed this reduction to the disturbance dynamo fields that damped the development of the EIA. Jain et al. [2010] studied TEC response to two geomagnetic storms at Bhopal (23.2° N), near the Indian EIA. These storms; 15 May 2005 (before noon: $Dst = -184 \text{ nT}$) and 24 August 2005 (afternoon: $Dst = -373 \text{ nT}$) had the main phase in the daytime. They found that during the main phase the TEC enhancement occurred during both the storms with August 24 storm showing two peaks. During the recovery phase of the storms no significant change in VTEC was observed. Kumar and Singh [2009] studied the effect of geomagnetic activity on TEC at Varanasi (25.28° N), in Indian EIA during May 2007 to April 2008, a solar minimum period. They found good correlation between monthly average in TEC and monthly average in $Kp$ index with $r = 0.82$. The $Dst$ showed poor correlation with $r = -0.03$. Bagiya et al. [2009] studied TEC variation at Rajkot (22.29° N), India, under a very intense geomagnetic storm on 24 August 2005 having daytime main phase. They found pre-storm TEC enhancement on 23 August and also TEC enhancement during the initial recovery phase (pre-midnight of 24 August) with respect to average quiet days’ value and then decreased in the post-midnight to daytime of August 25. Chauhan and Singh [2010] studied the effect of 10-11 November 2006 and 1-2 April 2007 geomagnetic storms on GPS-TEC at Agra (27.17° N), India, a low latitude station. They found that both the storms showed large enhancement in TEC two days after the occurrence of the storm (recovery phase) while no major change during the main phase. Thus, above storm studies show some positive and some negative effects on TEC. Each storm has its unique characteristics and therefore more work is required to have better understanding of low latitude TEC.

From the overview of these studies it is obvious that a reasonable amount of research has been done on low latitude region TEC studies, however, most of these studies, were carried out in the Northern hemisphere and in the Indian and American regions. Besides that, no observation of GPS-TEC has been reported from the South Pacific region. Thus, more work from the Southern hemisphere and the Pacific region
needs to be done. With Fiji being at the edge of the equatorial anomaly belt and in the
Southern hemisphere, provides a great location to carry out an investigation on TEC
variations in EIA region. This would help in better understanding of EIA and more
precise global mapping of TEC.

1.6.2 Scintillations

The phenomenon of scintillation was discovered by Hey et al. [1946] on radio
emission from Cygnus. Many researchers [e.g. Little and Maxwell, 1952; Koster and
Wright, 1960; Briggs, 1964; Aarons et al., 1964] studied radio star scintillations to
investigate ionospheric irregularities. The depth of amplitude scintillation was defined
in terms of scintillation index \( SI \) in dB by Whitney and Malik [1968] and Basu and
Basu [1989]. Since a lot of work has been done on scintillations, this review will be
limited to trans-ionospheric scintillations on signals from satellites and narrowed down
to emphasize on L-band studies.

The advent of satellites provided an opportunity to monitor ionospheric
scintillations continuously. In 1960s the ATS-3 satellite transmitting at 430 MHz
(UHF), 1295 MHz (L-band) and 7840 MHz (X-band), was used study the ionosphere
[Davies, 1980]. In 1966 the geosynchronous satellite ATS-6 was launched with the first
radio beacon signals specifically for ionospheric studies. ATS-6 had VHF beacon
signals at 40 MHz, 140 MHz, and 360 MHz [Davies, 1980]. Chandra et al. [1979]
studied scintillations of signals from ATS-6 satellite at Ootacamund (lat: 11.4° N, long:
76.7° E), Delhi, a low latitude station during 1975-76, a low solar activity period, and
found that nighttime scintillations were severe during summer months and weak during
equinox and winter months. Maximum scintillation occurrence was found in the
daytime. Davies [1980] reported that intense amplitude scintillations occurred in the
auroral zones and the equatorial region. Their temporal analysis showed that
scintillations were confined between 20:00 - 02:00 LT. Crane [1974] recorded
scintillations at 150 MHz (VHF) and 400 MHz (UHF) using US Navy Navigational
System satellites at the Millstone Hill Radar Facility during January 1971 to March
1973 and found that under magnetically disturbed conditions the amplitude
scintillations on the signals 150 and 400 MHz were nearly identical. He also found that
the scintillation fade rates under quiet conditions (at UHF 3.8 Hz and at VHF 6.2 Hz) were low when compared with the fade rates under disturbed conditions (at UHF 7.2 Hz and at VHF 9.2 Hz). The seasonal analysis of scintillation occurrence showed minimum number of scintillation events in spring and maximum number of events in fall (autumn).

The launch of P 76-5 satellite on 22 May 1976 provided with an opportunity to study the L-band (1239.171 MHz) scintillations [Fremouw et al., 1978]. Basu et al. [1988] studied amplitude scintillations recorded on 1.5 GHz signals from Marisat satellite during 1979-1986 (solar maximum to solar minimum period) at Huancayo, Peru (lat: 12.5° S and long: 75.2° W) at the magnetic equator and at Ascension Island (lat: 7.92° S, long: 14.41° W), USA. At Huancayo, the seasonal pattern during low solar activity period, 1985-86, showed clear equinoctial maximum in March and October. During high solar activity years of 1979 and 1980, only the occurrence of scintillations during vernal equinox was higher as compared to low solar activity years of 1985 and 1986. At the Ascension Island, scintillation was basically a pre-midnight phenomenon with peak occurrence in 22:00 LT to 00:00 LT interval. During the low phase of the solar cycle (1985-1986), there were virtually no L-band scintillations in May through August months. Basu and Basu [1989] provided a synopsis of global distribution of L-band scintillation during solar maximum and minimum periods showing maximum scintillation occurrence in the equatorial region and the auroral regions. They also found that scintillation was a nighttime phenomenon with higher fading rates during solar maximum as compared to solar minimum.

The availability of GPS systems in 1995 provided a cost effective and easier method of monitoring scintillation at L-band from any part of the Earth [Evans et al., 2002]. Since then, many researchers have studied L-band scintillations under various geophysical conditions [e.g. RamaRao et al., 2006a; 2006b; Muella et al., 2008; Adewale et al., 2012].

The results under the GAGAN (GPS Aided GEO Augmented Navigation) project with 18 stations all over India covering the geographic latitude of 8° to 32° N [RamaRao et al., 2006a; 2006b] during low solar activity period from January 2004 to July 2005 (LSSA) showed that L-band scintillations were associated with TEC
depletions of 5 to 15 TECU with maximum occurrence in the post-sunset to midnight (19:00 – 00:00 LT) period and peak at around 21:00 LT. Most scintillation events occurred during equinox season whereas almost no scintillation events were recorded during winter and summer seasons. RamaRao et al. [2006c] compared VHF (FLEETSAT: 244 MHz) and L-band (INMARSAT: 1.5 GHz as well as GPS: L1 1575.45 MHz) scintillations recorded during 1998-1999 (HSSA) and 2004-2004 (LSSA) period at Waltair (17.7° N), a low latitude station. They found that at both frequency bands, the scintillations occurred in the post-sunset hours during equinox and winter seasons in short-duration patches, whereas during summer the scintillations at GPS L-band were almost absent. Their comparison of scintillations at the two L-band frequencies (1.5 GHz and 1.57542 GHz) revealed a high degree of similarity in the occurrence features mostly in the post-sunset hours, and the scintillations observed at GPS L1 frequency were always associated with TEC depletions (plasma bubbles). Muella et al. [2008] analyzed the scintillations at seven stations in the Brazilian region; Boa Vista (2.8° N), Manaus (3.1° S), Cachimbo (9.5° S), C. Grande (20.5° S), C. Paulista (22.4° S), S. J. Campos (23.1° S) and Palmas (26.4° S) during October and November 2002. They found that highest level ($S_4$) of scintillations mostly occurred in the pre-midnight hours. Zou and Wang [2009] studied GPS ionospheric scintillations with $S_4 \geq 0.2$, at Guilin (25.29° N), China, near the northern crest of EIA, during low solar activity years, 2007 and 2008. They found that the amplitude scintillations seldom occurred in the nighttime (18:00 – 06:00 LT) during both the years. Only three nighttime scintillation events were observed; 1 January 2007, 16 April 2007 and 5 February 2008, while strong amplitude scintillations with $S_4 > 0.4$ occurred quiet often in the daytime (06:00 – 18:00 LT). They also reported that the nighttime amplitude scintillations were associated with phase and TEC fluctuations. However, daytime strong amplitude scintillations with $S_4 > 0.4$ were usually associated with phase scintillations, whereas weak amplitude scintillations ($0.2 \leq S_4 < 0.4$) and phase scintillations did not occur concurrently. Adewale et al. [2012] studied scintillations and TEC at Lagos (6.5° N), Nigeria, during February 2010 and August 2010 and found that the amplitude scintillation events occurred both in the night and day times. Though, the $S_4$ increased during post-sunset hours, the daytime amplitude scintillations with $S_4 > 0.4$
were also observed. They also found that nighttime amplitude scintillations were always associated with phase scintillation and TEC fluctuations, noting that VTEC depletions between 21:00 and 00:00 LT produced both amplitude and phase scintillations. Their seasonal analysis showed maximum scintillation occurrence in the equinox.

Spatial variation of scintillation activity has also been studied. Thomas et al. [2001] using data recorded at five GPS receiver stations in Australia and South East Asia; Marak Parak (6.31° N), Malaysia, Pontianak (0.00°), Indonesia, Vanimo (2.4° S), PNG, Parepare (3.98° S), Indonesia, and Darwin (12.4° S), Australia, during 1998-1999 reported that the scintillation activity was lower at Darwin (south of anomaly region) in comparison with sites located between the magnetic equator and the anomaly crest (Marak Parak, Pontianak and Parepare) and scintillation activity was higher at the anomaly crest than at the magnetic equator. Under the GAGAN network of 18 GPS stations spread over geographic latitude of 8° to 32° N in India, RamaRao et al. [2006a] showed that during low solar activity period of January 2004 to July 2005, depth of scintillations ($S_4$) and occurrence were higher at EIA stations as compared to equatorial stations. The scintillations, in general, were weak (3-6 dB) with almost no strong (> 10 dB) scintillations at equatorial stations. Muella et al. [2008] examined scintillation activity at seven stations in Brazil; Boa Vista (2.8° N), Manaus (3.1° S), Cachimbo (9.5° S), C. Grande (20.5° S), C. Paulista (22.4° S), S. J. Campos (23.1° S) and Palmas (26.4° S) during the months of October and November 2002. They found that scintillation occurrence and intensity appear to be higher at low latitude stations as compared to the stations located closer to the dip equator. Though scintillations were mostly concentrated in the local pre-midnight hours, but at low latitudes some scintillation events occurred until 03:00 LT. They also found cases of moderate to strong scintillation events not associated with TEC depletions. Paznukhov et al. [2012] studied the GPS L-band scintillations in the African sector under the Scintillation Network Decision Aid (SCINDA) using data from three SCINDA stations namely; Cape Verde (16.7° N), Lagos (Nigeria: 6.5° N) and Kampala (Uganda: 0.3° N) recorded during 2010. They found that overall the GPS scintillations were weak with rare occurrence of events with $S_4 > 0.25$. Scintillations were mainly observed during the equinoctial season.
Very little work has been done on effects of solar activity on GPS L1-band scintillations. Kumar and Gwal [2000] studied solar activity variations (sunspot number $R_z$) of VHF (244 MHz) nighttime scintillation at Bhopal (25.5° N, near the Indian EIA crest), India, using three and a half years of data; September 1988 – December 1991. They reported that peak scintillation activity occurred at around 22:00 LT with 20% in 1989 ($R_z = 154$), 15% in 1990 ($R_z = 145$), 13% in 1991 ($R_z = 121$) and 10% in October 1992 till February 1993 ($R_z = 98$). An interesting feature found was that, though the scintillation activity changed with solar activity, the equinoctial maxima was always present in every year from 1989-1991. DasGupta [2006] studied amplitude scintillations on L-band signal from INMARSAT (1.5 GHz) and GPS (1575.42 MHz) as well as VHF from FLEETSAT (244 MHz) recorded during 1996 to 2000 (nearly half solar cycle), at Calcutta (22.58° N), located near the Indian anomaly crest and found that during the low solar activity years of 1996-1997 scintillations at L-band with $SI \geq 10$ dB were absent and during 1997-1998 scintillations with $SI \geq 20$ dB were absent. During the period of maximum sunspot number (March 2000), DasGupta found that the higher hourly percentage occurrences of 39% for $SI \geq 10$ dB and 37% for $SI \geq 20$ dB for March 2000, the period of sunspot maximum. He also found that the increase in both percentage occurrence and intensity of scintillation at L-band with sunspot number was very much apparent with maximum occurrence of ~30% with fade depth greater than 30 dB in March 2000. The very less work on solar cycle dependence of scintillation occurrence is lucid and more continuous recording of GPS signals is needed to study the solar activity dependence of scintillations.

Scintillation occurrence during magnetically disturbed conditions and magnetic storms has also been of interest of many researchers [e.g. Aarons et al., 1997; Beach and Kitner, 1999; DasGupta, 2006; Priyadarshini and Singh, 2011]. Aarons et al. [1997] studied GPS L-band amplitude and phase scintillations at seven stations around the magnetic equator covering 5-6° N and 6-32° S under intense and very intense magnetic storms that occurred during November 1993 to October 1995. They found that during storms with main phase in the pre-midnight, phase scintillations occurred from pre-midnight till post-midnight periods in the equatorial stations, while post-midnight amplitude scintillations occurred at the anomaly stations. With storms having main
phase in the daytime, phase scintillations during the daytime were recorded at equatorial stations and later post-midnight amplitude scintillations were found at the anomaly stations showing that phase scintillation near the magnetic equator while amplitude scintillations more common in the anomaly region. Beach and Kitner [1999] compared GPS scintillations and TEC variations recorded during April 1997 at Ancon (11.77° S), Peru, in the equatorial region and found that scintillations did accompany TEC fluctuations, however, at times TEC showed fluctuations but no scintillations were observed. DasGupta [2006] analyzed the L-band scintillations at INMARSAT (1.5 GHz) signals, GPS (1575.42 MHz), and at VHF signals from FLEETSAT (244 MHz) recorded at Calcutta (22.58° N), located under the Indian anomaly crest, during 1996 to 2000 (nearly half solar cycle). DasGupta found that during the equinoctial months, the scintillation occurrence was less during magnetically active periods as compared to quiet periods except in April 2000. During the local summer months (Indian Time) May-July (like May 1998, May 1999, July 2000), the scintillation occurrence was more under magnetically active period than under the quiet periods. He also analyzed the scintillation occurrence under 17 intense magnetic storms (-200 nT ≤ Dst < -100 nT) occurred during 1996-2000 and found that scintillation events were seen in 23.5% storms (4 out of 17) and absent in the rest 76.5% (13 storms). When these storms were categorized seasonally, he found that during the equinoctial months, out of a total 10 storms, only 1 storm showed scintillation occurrence. In summer (May-July), 50.0% (2 out of 4) of the storms showed scintillations while in winter (November-January), 33.3% (1 out of 3) of storms exhibited scintillations. Priyadarshni and Singh, [2011] analyzed the GPS scintillations at Varanasi (25.30° S), India, a low latitude station, under the geomagnetic storm of 3-5 August 2010 which had the main phase in the pre-midnight till post-midnight period with two minimum Dst at 23:30 LT on August 3 and another one at 05:30 LT on August 4. They found no scintillation event during main phase (pre-midnight to post-midnight period) and recovery phase of this storm indicating the inhibition of scintillation activity during geomagnetic storm.

Very little work [Kumar et al., 2007; Thomas et al., 2001] on scintillations has been done in the South Pacific region. Kumar et al. [2007] studied scintillations on C-band at Suva, Fiji while, Thomas et al. [2001] studied GPS scintillations in Australia
and in South East Asian stations. Present study would be the first study of L-band scintillation carried out at Suva, Fiji. Our location, Suva, is at the edge of the anomaly crest and provides an excellent opportunity to study the morphology of L-band scintillations at the outer edge of the southern equatorial anomaly.

1.7 Objectives

The main objectives of this work are:

1. To study diurnal, monthly, seasonal and annual variation of TEC and the day-to-day variability of TEC during the period of January 2010 -December 2010.
2. To study monthly, seasonal and annual variation of weak, moderate and strong L1-band scintillations during the period of January 2010 -December 2010.
3. Investigate geomagnetic activity effect on TEC and scintillation by comparing the data on quiet (Q) and disturbed (D) days.
4. Analyze the TEC and scintillations during disturbed Space Weather conditions (Magnetic storms) during January 2010-December 2011.

1.8 Thesis Organization

This thesis is composed of six chapters, which are compiled in order to accomplish the objectives of this work. Chapter 1 is the introduction which gives a brief overview of the main subject of this work. It describes the ionosphere and the anomaly region with the processes involved in the development of irregularities in the equatorial and low latitude ionosphere. The synopsis of geomagnetic storms on ionospheric effects is also outlined. With that a concise account of GPS and its functioning is given following that is the literature review on the TEC and scintillations.

The chapter 2 outlines the experimental setup along with the data analyzing techniques employed in this work. The details of the two main parts of the setup; the GSV 4004B receiver and the GPS 702 L1/L2 antenna are described. In data analysis the procedures used to analyze TEC and scintillation are thoroughly explained.
Chapter 3 deals with the morphological study of TEC at Suva. The day-to-day variability of TEC has also been studied. In addition, the diurnal, monthly, seasonal and annual TEC variations have been presented.

Chapter 4 presents the morphological study of L-band scintillations at Suva. The diurnal, monthly, seasonal and annual occurrences of weak, moderate and strong amplitude scintillations are presented. The scintillation occurrence has been studied for different periods of the day namely; daytime, pre-midnight and post-midnight. The associations of strong amplitude scintillations with TEC, C/No and phase scintillations have also been studied.

In chapter 5 the effects of geomagnetic disturbances on TEC and scintillations have been presented by separating the TEC and scintillation data on Q- and D-days of each month. The effects of storms of different strengths, moderate, intense and very intense, divided under different categories (A, B and C) on TEC and scintillations have been presented.

Chapter 6 finally summarizes the important findings of this work and gives some suggestions for future work.
Chapter 2

Description of Experimental Setup

The L1 (1575.42 MHz) and L2 (1227.60 MHz) band signals from the Global Positioning System (GPS) satellites recorded using dual frequency receivers have been utilized to study the spatial and temporal changes in the total electron content (TEC) of the ionosphere. This chapter gives an outline of the GPS experimental set-up employed in this work. The main components used are the GPS 702 L1/L2 antenna and the GSV 4004B receiver supplied by GPS Silicon Valley, USA. The dual frequency GPS Ionospheric TEC and Scintillation Monitor (GISTM), model GSV 4004B, was installed under a research project, at our site in Suva (lat., 18.08° S and long., 178.26° E) in January 2010. The data recording started on 15 January 2010 at 12.18 pm local time (LT). The general description of different components of experimental set-up is given in the next section. This is followed by the procedure used in this work for recording and analysis of the data.

2.1 GPS Ionospheric TEC and Scintillation Monitor (GISTM)

The experimental set-up consists of GPS 702 L1/L2 antenna connected with GSV 4004B unit which is interfaced to a PC for continuous data acquisition and storing as shown in Figure 2.1. This type of receiver has been used by many researchers for ionospheric study [e.g. Bagiya et al., 2009; RamaRao et al., 2006a; Chauhan et al., 2011; Adewale et al., 2012]. The description of the individual components is as follows: This receiver GSV 4004B package has been specifically designed for the purpose of recording of TEC and ionospheric scintillations on L1 frequency (1575.42 MHz). The package consists of NovAtel’s EuroPak-3M enclosure that houses the GPS receiver and a low noise oven controlled crystal oscillator (OXCO) required for monitoring phase scintillations. The receiver can track up to 11 GPS satellites transmitting L1 and L2 frequency. This offers a great opportunity to study the TEC variation approximately 15° north and south of the receiving station in Suva.

The GSV 4004B has 24 channels; 22 channels are used to receive L1 and L2 band signals from the satellites simultaneously. The 23rd channel is used for
measurement of local background noise (C/No) and scintillation index $S_d$ correction factors. The 24th channel is configured to track Satellite-based augmentation system (SBAS) which measures phase and amplitude at a sampling rate of 50 Hz and code/carrier divergence at 1 kHz for each satellite being tracked on L1 [GPS Silicone Valley, 2007]. Then it computes TEC from combined L1 and L2 pseudorange and carrier phase measurements. The pseudorange measurements are less precise than the carrier phase measurements, so it was used only for detection of cycle slips and to estimate and remove ambiguity terms in the phase. Generally, signal to noise ratio on a geomagnetically quiet day is 36 dB-Hz for GSV 4004B unit.

The GSV 4004B unit works with a DC power supply of 9 to 18 volts with power consumption of 6 watts. The power supply connected in this case was 12 volts. The external oscillator has input frequency of $10 \pm 0.5$ MHz with signal level of 0 - +13 dBm. The Antenna’s low noise amplifier (LNA) requires a power input +5 VDC with a maximum current of 100 mA from the receiver. According to specifications EuroPak-3M can operate in environmental temperatures from -20 to +60° C having humidity of 95% non-condensing. Our experimental set was operated in an air-conditioned room with regulated temperatures of 22° C.

![Figure 2.1: GPS data recording set-up at the University of the South Pacific, Suva, Fiji.](image_url)
GPS 702 antenna is an active antenna designed by NovAtel to receive at the GPS L1 and L2 signals. Before installing the antenna, the site selection was done according to the GPS Silicone Valley [2007], manual and specifications. The guidelines stated, required for an unobstructed line-of-sight from horizon to horizon at all bearing and elevation angles. It needed to be far from reflective surfaces, especially water bodies. In view of these requirements, the best suitable place was the roof of the Physics building (N258 Block). This site is unobstructed from the horizon and also away from reflective surfaces as shown in Figure 2.2.

The antenna was mounted with the thread of 20 mm. The thread was aligned with the metal adapter on the bottom of the antenna and the antenna was rotated clockwise until it was securely mounted on to the mount as shown in Figure 2.3a. A wrench was then used to tighten the adapter to the mount. The base of the mount was then firmly fixed onto the roof with nut and bolts. The dust cap from the antenna’s TNC connector was removed and the male TNC connector of the coaxial cable was attached to the antenna’s connector as shown in Figure 2.3b. Then, the other end of the coaxial cable was inserted into the GSV 4004B receiver. Figure 2.4 shows the mechanical diagram with detailed dimensions of GPS 702 antenna.
Figure 2.3: a) GPS antenna mounting, b) Antenna and cable connection. Reproduced from GPS Silicone Valley [2007], manual.

Figure 2.4: Mechanical drawings of the GPS 702 antenna: a) Top View. b) Side View – Dimensions in mm. c) Bottom View - Dimensions in mm. Reproduced from GPS Silicone Valley [2007], manual.

GPS 702 antenna has been designed to withstand the elements like rain, snow and dust. The antenna type is an aperture coupled slot array antenna that provides superior multipath rejection and is lightweight, waterproof with dimensions that enable
it to be mounted with ease as shown in Figure 2.4 a-c [GPS Silicone Valley, 2007]. The beam width is an important parameter in characterizing any antenna. The polar diagram in Figure 2.5 shows the radiation pattern of GPS 702 at L1 and L1 frequencies. The 3 dB points are defined as the half power beam width (HPWB). For this antenna the HPWB at both L1 and L2 as described in specification is 80° with half power band pass of L1/L2 -15 MHz to L1/L2 +30 MHz. The nominal impedance is 50 Ω. In any transmission line not all the power is absorbed and a part of it is reflected back. These incident and reflected signals mixes up forming a voltage standing wave pattern characterized by voltage standing wave ratio (VSWR). The VSWR is a ratio of maximum to minimum voltage and is an indicator of signal being reflected back [Sadiku, 2000]. The GPS 702 antenna used here has VSWR ≤ 2.0:1. Low noise amplifier (LNA) works at an input voltage of 4.5 – 18.0 VDC and current of 35 mA [GPS Silicone Valley, 2007]. The LNA converts microwave, L1 and L2, signals into electrical currents and amplifies by 27 dB. Operating temperature of antenna is between -40° C to +85° C.

![Elevation gain pattern of GPS 702 antenna](image)

**Figure 2.5:** Elevation gain pattern of GPS 702 antenna [NovAtel Inc., 2012].

Good antennas incorporate left hand polarization (LHP) rejection. Multipath signals cause a change in the polarization during the refraction and reflection process, therefore, multipath signals are LHP. If a GPS antenna is well designed for right hand polarization (RHP), then LHP multipath signals will automatically be attenuated somewhat during the induction into the antenna [NovAtel Inc., 2012]. To further
enhance performance, antennas can be designed to increase the rejection of LHP signals as has been done with this antenna. The gain patterns of RHP and LHP signals at both L1 and L2 are also shown in Figure 2.5.

Antenna Feedline Coaxial cable was used as the antenna feedline and is a vital component of any ground station in the communication. A good feedline transmits signals from the LNA to the receiver with minimal loss and reduces radio frequency (RF) interference from other stray sources. The coaxial cable (RG303/U) was also supplied with the components by GPS Silicone Valley, USA, which has an impedance of 50 \( \Omega \). It has 0.95 mm of center conductor made of steel coated with copper and silver. The outer conductor is 3.6 mm silver plated copper covering the Polytetrafluoroethylene (PTFE) dielectric of 2.95 mm diameter [Huber and Suhner, 2007]. The experimental set-up used is shown in Figure 2.6a with the rear view of GSV 4004B for connections with the antenna and the PC (Figure 2.6b).

Figure 2.6: a) Experimental set-up, b) GSV 4004B Connections.
2.2 Data Recording and Analysis

The GPS experimental system described in section 2.1 has been used to record ionospheric TEC and scintillations. The one year worth of data recorded using the GISTM receiver designed by NovAtel has been analyzed. The receiver firmware includes the ability to measure carrier phase as well as the signal power at a sampling rate of 50 Hz. Special logs are generated for the output of these indices. The high rate data can be logged either as raw or detrended data. A series of distinct procedures were taken at various stages in the analysis of raw data which are outlined in the following sections.

2.2.1 TEC data recording

The GSV 4004B system initializes automatically upon power up and commences on tracking satellites using default information. In order to suite our location the clocktime was adjusted and the receiver bias (Sin TEC Calibration) of -73.933 TEC units (TECU) was also entered. Each receiver-satellite pair has a different bias. In our case, the receiver part of the bias of -73.933 TECU was supplied by the manufacturer by calibrating the receiver against Wide Area Augmented System (WAAS). For satellite biases, the 32 offset values given were entered during initialization of the receiver using the CP-Offset command. As our main aim of the study was to investigate the variations in TEC, this approach is satisfactory. This same technique was instigated by Bagiya et al. [2009] and Chauhan et al. [2011]. Recently (August 2012), a new technique for determining receiver biases in GPS derived TEC was instigated in the auroral region using the Canadian Advanced Digital Ionosonde (CADI) network [Themes et al., 2012]. This study revealed that biases largely depend on the receiver and the location of the receiver. Such technique may also be application to the low latitudes which has not been the part of this study. We have used the manufacturer’s bias values as used by various authors at the low latitudes. In the absence of such biases the VTEC values could be different than absolute values but the morphological study and trends that we have acquired would still be the same.

To log the data, SLOG program was used. This software comes with the package. SLOG is a windows based code that is executed using the Command Prompt.
In our case SLOG was programmed to produce a new file everyday and stored these files in a folder named according to GPS weeks. At the end of each GPS week a new folder is created by the program itself and then the respective daily files are stored in it. The GPS days begins from Sunday (0) to Saturday (6).

TEC is a measure of the number of electrons along the path of the signal from the satellite to receiver in a 1 m$^2$ cylindrical shell. The measurements are affected by the elevation angle of the satellite from the station and ionospheric height [Komjathy and Langley, 1996]. A TEC unit is defined as $1 \times 10^{16}$ electrons m$^{-2}$. Signals received from satellites directly above the station were used as vertical TEC (VTEC). The satellite signals other than the overhead provide the Oblique TEC (OTEC) or Slant TEC (STEC). The STEC is proportional to the ionospheric delay between L1 and L2 signals.

The data recording program (SLOG) uses this delay and takes care of the instrumental biases before final STEC values are estimated using the formula [GPS Silicone Valley, 2007]:

\[
\text{STEC} = [9.483 \times (P_{R_{L2}} - P_{R_{L1}} - \Delta_{C/A-P,PRN}) + TEC_{RX} + TEC_{CAL}] \quad (2.1)
\]

where:
- $P_{R_{L2}}$ - is the L2 pseudorange in metres
- $P_{R_{L1}}$ - is the L1 pseudorange in metres
- $\Delta_{C/A-P,PRN}$ – is the input bias between SV C/A- and P-code chip transition in metres
- $TEC_{RX}$ - is the TEC result due to internal receiver L1/L2 delay
- $TEC_{CAL}$ - is the user defined TEC offset (in this case it is -73.933 TECU)

The receiver acquires data at the sampling rate of 50 Hz from all the satellites being in sight. Each data block contains 50 sets of data; the first set is at time specified Time of Week (TOW), the second set at TOW + 0.02 seconds and so on. Then it automatically reduces these raw measurements every minute on the minute and converts it into a convenient ASCII format which is stored at an interval of 60 seconds in files with extension .GPS such as 1566_5_00_NYM07470021.GPS.
2.2.2 Scintillation data recording

The depth of amplitude scintillation is described by the $S_4$ index. The raw $S_4$ index is de-trended (by normalization) with the measurements averaged over 60 second intervals. This measurement is also done at the rate of 50 Hz as for TEC and then recorded at 60 second intervals. Measured $S_4$ or the total $S_4$ at L1 that is logged by the receiver has the effect of ambient noise and multipath effects. The $S_4$ computation is done using the signal power, as given by the following equation, at one minute intervals.

$$S_4 = \frac{<Sl^2>-<Sl>^2}{<Sl>^2}$$ (2.2)

where: $Sl$- is the signal intensity measured by the receiver at the rate of 50 Hz.

$<>$- indicates the expected value of the quantity enclosed over a full minute.

Since the variance of the $Sl$ is normalized by the square of the average value of $Sl$, the resulting total $S_4$ is a dimensionless number with a theoretical upper limit of 1.

The receiver also records raw code/carrier divergence every second. Code/carrier divergence is the difference between the code and carrier pseudorange. The multipath interference can produce scintillations, therefore, average and standard deviation of the code/carrier divergence are then computed every minute. The raw measurements are detrended with a 6th order Butterworth high pass filter with a cut-off of 0.01 Hz. These values are indicative of the multipath and noise activity and can be used to distinguish between $S_4$ due to multipath and noise and $S_4$ due to real scintillations, since there is no code/carrier divergence due to scintillations. The SLOG code also computes the correction to the total $S_4$ and records as $S_4 \text{ Cor}$. The correction due to the ambient noise is applied based upon the average raw 1-Hz C/No values over the same 60 second (one minute) interval [GPS Silicone Valley, 2007]. The $S_4$ and $S_4 \text{ Cor}$ are logged simultaneously by SLOG.
2.2.3 VTEC analysis

The STEC data stored are in SLOG files in .GPS format on a daily basis. The daily files were then converted using the offline utility program, Parseismr. The Parseismr is executed under Command Prompt and converts the .GPS files first into text (.txt) formats and then delimited and saved as MS Excel (.xls) format. To convert into text format, the executable Parseismr is copied into each folder created by SLOG and then DOS Command is used to execute Parseismr which converts the respective file into .txt format. The command used is given as: Parseismr.exe <prn><Inputfile><Outputfile>. An example of this is:

D:\GPSDATA\1568>Parseismr.exe#all#1568_0_00_NYM07470021.GPS#1568_0_00_NYM07470021.txt.

Note # represents a blank space. This implies the data is in D drive, then DOS opens the folder GPSDATA and then the folder 1568. After opening this, Parseismr is executed for all PRN. The input file is 1568_0_00_NYM07470021.GPS and the output file is 1568_0_00_NYM07470021.txt. This process was carried out for each single file created, that is, for each day. The MS Excel was used to open these text files one at a time and then the comma delimited was carried out to have data in their respective rows and columns in .xls format. The final format of the data can be seen in Table 2.1. It also shows the meanings of each abbreviation used in the columns and their respective units.

Table 2.1: Parseismr extracted data fields with abbreviations and units. Adapted from GPS Silicon Valley [2007].

<table>
<thead>
<tr>
<th>Excel Column</th>
<th>Data</th>
<th>Abbreviations Used</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Week Number (WN)</td>
<td>WEEK</td>
<td>N/A</td>
</tr>
<tr>
<td>B</td>
<td>Time of Week</td>
<td>GPSTOW</td>
<td>Seconds</td>
</tr>
<tr>
<td>C</td>
<td>Pseudo Random Noise</td>
<td>PRN</td>
<td>N/A</td>
</tr>
<tr>
<td>D</td>
<td>Receiver Status</td>
<td>RxStatus</td>
<td>N/A</td>
</tr>
<tr>
<td>E</td>
<td>Space Vehicle (SV) Azimuth Angle</td>
<td>Az</td>
<td>Degrees</td>
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<td>F</td>
<td>Space Vehicle (SV) Elevation Angle</td>
<td>Elv</td>
<td>Degrees</td>
</tr>
<tr>
<td>G</td>
<td>L1 Carrier to Noise Ratio</td>
<td>L1CNo</td>
<td>dB-Hz</td>
</tr>
</tbody>
</table>
The data were then sorted and truncated from GPS weeks to make it par with the Gregorian calendar and local time. All the rows with data having a Lock Time at L1 and L2 for less than 240 seconds were eliminated. The Lock Time indicates how long the receiver has been locked to the carrier phase on L1 (L1 Lock Time) and on L2 (L2 Lock Time). The phase detrending filter has to reinitialize whenever lock is lost thus all the parameters needs to be discarded to allow the detrending filter to resettle. In this case 240 seconds have been allowed. Further smoothing was done by eliminating data with very large sigma phase (60 sec sigma phase) values.

Data were again sorted according to the column of elevation angles in ascending order. The rows with elevation angle less than 50° were also eliminated. The selection

<table>
<thead>
<tr>
<th>Column</th>
<th>Description</th>
<th>SI Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>Total $S_d$</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>Correction to total $S_d$</td>
<td>$S_d$ Cor</td>
</tr>
<tr>
<td>J</td>
<td>1-second Sigma Phase</td>
<td>1SecSigma</td>
</tr>
<tr>
<td>K</td>
<td>3-second Sigma Phase</td>
<td>3SecSigma</td>
</tr>
<tr>
<td>L</td>
<td>10-second Sigma Phase</td>
<td>10SecSigma</td>
</tr>
<tr>
<td>M</td>
<td>30-second Sigma Phase</td>
<td>30SecSigma</td>
</tr>
<tr>
<td>N</td>
<td>60-second Sigma Phase</td>
<td>60SecSigma</td>
</tr>
<tr>
<td>O</td>
<td>Average of code to carrier divergence</td>
<td>Code-Carrier</td>
</tr>
<tr>
<td>P</td>
<td>Sigma of code to carrier divergence</td>
<td>C-CStdev</td>
</tr>
<tr>
<td>Q</td>
<td>TEC at TOW – 45</td>
<td>TEC45</td>
</tr>
<tr>
<td>R</td>
<td>ΔTEC from TOW – 60 to TOW – 45</td>
<td>TECRate45</td>
</tr>
<tr>
<td>S</td>
<td>TEC at TOW – 30</td>
<td>TEC30</td>
</tr>
<tr>
<td>T</td>
<td>ΔTEC from TOW – 45 to TOW – 30</td>
<td>TECRate30</td>
</tr>
<tr>
<td>U</td>
<td>TEC at TOW – 15</td>
<td>TEC15</td>
</tr>
<tr>
<td>V</td>
<td>ΔTEC from TOW – 30 to TOW – 15</td>
<td>TECRate15</td>
</tr>
<tr>
<td>W</td>
<td>TEC at TOW</td>
<td>TEC0</td>
</tr>
<tr>
<td>X</td>
<td>ΔTEC from TOW – 15 to TOW</td>
<td>TECRate0</td>
</tr>
<tr>
<td>Y</td>
<td>L1 Lock Time</td>
<td>L1 LockTime</td>
</tr>
<tr>
<td>Z</td>
<td>Channel Status</td>
<td>ChanStatus</td>
</tr>
<tr>
<td>AA</td>
<td>L2 Lock Time</td>
<td>L2 LockTime</td>
</tr>
<tr>
<td>AB</td>
<td>L2 Carrier to Noise Ratio</td>
<td>L2 CNo</td>
</tr>
</tbody>
</table>
of data for elevation angle greater than 50° reduces the troposphere effect as discussed by Unnikrishnan and Ravindran [2010] and RamaRao et al. [2006a]. Tropospheric effect is the bending of rays due to increased length of the signal path in the Earth’s atmosphere consisting of air and water vapor with different refractive indices. The refractive index of troposphere is greater than unity and that of ionosphere is less than unity and as a result refraction and absorption occur at low elevation angles [Hopfield, 1976].

The TEC obtained by GISTM is referred to as Slant TEC (STEC) and is dependent on the ray path geometry through the ionosphere as discussed before. STEC is defined as the total electron content along the line-of-sight from the satellite to the receiver while, Vertical TEC (VTEC) is the total electron content along the vertical path from the receiver. Thus, STEC needs to be converted to VTEC which is independent of the ray path. The VTEC was computed using the STEC and elevation angles. The VTEC is obtained by taking the projection from the slant to vertical using the Thin Shell Model technique given by Klobuchar [1987] and Mannucci et al. [1993].

\[
VTEC = STEC \times \cos \theta \times \frac{R_E \cos \theta}{R_E + h_{max}}
\]

where: STEC - is the slant total electron content
\( R_E \) – mean radius of the Earth (6378 km)
\( h_{max} \) - Ionospheric pierce point height (IPP = 350 km)
\( \theta \) – satellite elevation angle at the ground station

The ionospheric pierce point (IPP) is the point of intercept of the line-of-sight ray and the thin shell of ionosphere at an altitude ‘h’ above the Earth’s surface. The IPP has been taken as the altitude of 350 km for our station in Suva. RamaRao et al. [2006a] have justified the IPP to be 350 km altitude for the low latitudes in the Indian region. Our location in Suva is in the opposite hemisphere to their stations in the Indian region, however, the latitude of Suva 18.08° S falls well in the low latitudinal belt. RamaRao et al. [2006b] also suggested that IPP of 350 km was valid only for elevation angles greater than 50°. Hence, also in this work the cut-off elevation angle has been taken as 50°. The above analyses were done using MS Excel data files. Since the graphing utility
in Excel is not capable of processing very large amount of data and has limited amount of smoothing capacity, the data was further analyzed using a Matlab code.

The data for each day was imported to Matlab using the tool “uiimport”. The data in each column was stored in Matlab as separate matrices. A “SplineToolbox” in Matlab was used to smooth the VTEC data for each day. In order to do this a set of codes were written, and the full codes are given in Annexure I. The spline uses “CSAPS” command. CSAPS(X,Y) returns the smoothed cubic spline form for the data X,Y (which are the X and Y values) in the “pp” form. The returned “pp” form is a structure containing four arrays. The smoothing spline approximates, at the data site X(j), the given data value Y(:,j), j = 1: length(X) are matrices. The data used could be scalars, vectors, matrices, or even ND-arrays. All the data points with same place are replaced by their (weighted) average, for smoothing purposes. This smoothing spline function minimizes as

\[ P \sum_j W(j) |Y(:,j) - f(X(j))|^2 + (1-P) \int |D^2 f|^2. \]  

Here, the sum is over \( j=1: \text{length}(X) \); \( X \) and \( Y \) are the result of replacing any data points with the same site by their weighted average and with its weight the sum of the corresponding weights;

the integral is taken over the interval \([\text{min}(X) .. \text{max}(X)]\)

\(|z|^2\) is the sum of the squares of the entries of \( z \); where \( z = Y(:,j) - f(X(j)) \),

\(D^2 f\) is the second derivative of the function \( f \), and

\(W = \text{ones}(	ext{length}(X),1)\) is the default value for \( W \).

The smoothing parameter \( P \) is chosen, in an ad-hoc fashion and in dependence on \( X \), as explained in the next paragraph. One can supply a specific value for \( P \) using \( \text{CSAPS}(X,Y,P) \) instead.

When \( P \) is 0, the smoothing spline is the least-squares regression of straight line (best fit straight line), while at the other extreme when \( P \) is 1, it is the ‘natural’ or variational cubic spline interpolant. The region of transition between these two extremes (\( P = 0 \) to \( P = 1 \)) is a fairly small range of values for \( P \) and its location strongly depends on the data sites. It is in this small range that \( P \) is chosen when it is not supplied, or
when an empty P or a negative P is an input. If P > 1, then the corresponding solution of the above minimization problem amounts to a roughening rather than smoothing.

In our case the P was 0.01 which is very close to the least square regression of the straight line. The command used was of the form CSAPS(X,Y,P,XX,W). This returns depending on whether or not XX is empty, the ppform, or the values at XX, of the cubic smoothing spline for the specified weights W. Any negative weight is replaced by 0, that makes the resulting smoothing spline independent of the corresponding data point. When data points with the same site are averaged, their weights are summed. An example of the full command used is given as:

```matlab
pp = csaps(local time,VTEC, .01, [], [ones(1,3053)]);
```

where local time is the X values, VTEC is the Y values, P is 0.01, [ ] – shows returned form of the function is a matrix, and [ones(1,3053)]- is the matrix on which csaps operates which in this case is a $1 \times 3053$ matrix.

The returned pp or smoothed data were stored into appropriate matrices for plotting purposes. The plots of original VTEC from MS Excel and smoothed VTEC using CSAPS command is shown in Figure 2.7 below which compare very well.

![Figure 2.7: Variations of VTEC on 17 January 2010. The top panel a) shows the VTEC from every satellite in view while the bottom panel b) shows its respective smoothed VTEC using Matlab code.](image-url)
Note that the straight lines do not have any values and is replaced by “Nan” in Matlab meaning no values are in place. These lines appear since the satellite is visible at certain times of the day and the data from each satellite are linked. As the values are replaced by “Nan” it does not affect the overall smoothing of the data. In the raw data there seems to be hourly short-lived harmonics as in panel (a) of Figure 2.7. These emerged when the slant TEC (STEC) was converted to vertical TEC (VTEC). The Thin Shell Model technique used for the conversion (Equation 2.3) is dependent on the satellite elevation angle ($\theta$) at the ground station. So as the elevation angle increases, the VTEC also increases and as the elevation of the satellite decreases, the VTEC decreases which accounts for the peaks from each satellite.

Day-to-day variability of TEC has been studied by plotting the VTEC for all the days of a particular month in the same Figure. These mass plots were done for all the months of 2010 separately. The monthly averages were also computed and plotted in the same mass plots. For seasonal study the monthly averages were used. Since, Fiji has only two major seasons called Hot and Wet and Cold and Dry [Kumar, 2003], the months were sorted according to the seasons they fall into and the monthly averages were again averaged to obtain the seasonal variation. Hot and Wet season includes the months of January, February, March, April, November, December and Cold and Dry season includes May, June, July, August, September, October.

To study the geomagnetic storm effect on TEC, first we considered the SSC type storms. SSC stands for sudden storm commencement and is characterized by sudden increase in the horizontal component of the Earth’s magnetic field ($H$) due to compression of the geomagnetic field. The SSC details were obtained from National Geophysical Data Center (NGDC), National Oceanic and Atmospheric Administration, US Department of Commerce, USA website: ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUDDEN_COMMENCEMENTS/STORM2.SSC. The strengths of the storms are determined from the $Dst$ index. $Dst$ is storm time disturbance, comprising of the disturbance field produced by the ring current, the tail current and the magnetopause boundary current. This index was retrieved from World Data Centre (WDC) for Geomagnetism, Kyoto University, Japan website: http://wdc.kugi.kyoto-u.ac.jp/dst_realtime/presentmonth/index.html. During the main
phase of the storm, the $Dst$ decreases to its minimum value. This minimum $Dst$ attained by the storm was used to classify the geomagnetic storms as follows: very intense $Dst < -200$ nT, intense $-200$ nT $\leq Dst < -100$ nT, and moderate $-100$ nT $\leq Dst < -50$ nT

[Kumar et al., 2005].

In order to study the Storm Gradual Commencement (SGC) type of storms, we selected the storm days provided that particular day was a disturbed day according to five international disturbed days (obtained from the WDC website: http://wdc.kugi.kyoto-u.ac.jp/cgi-bin/qddays-cgi) and having a minimum $Dst$ less than -50 nT. The SSC data on NGDC website were only available till January 2011, therefore, we used the same criteria as above to select the storms for 2011. The storms for 2010 and 2011 were taken into account for this study. An example of moderate storm on 11-12 October 2010 is shown in Figure 2.8 (LT = UT + 12 hrs). The storm onset is indicated by SSC, the main phase and the recovery phase as indicated on the figure.

![Figure 2.8: Variation of $Dst$ index for storm of 11-13 October 2010.](image)

To study the storm effect on VTEC, the VTEC values were plotted a day before the storm, storm day and for a day after the storm. For better comparison and to study the storm effect on VTEC more closely, five international magnetically quiet days of the month in which storm occurred were selected (according to the data from the WDC site: http://wdc.kugi.kyoto-u.ac.jp/cgi-bin/qddays-cgi). The VTEC on these quiet days were averaged and plotted with the VTEC values on storm day and one day before and
one day after the storm. Main phase of the storm, whether it falls in the day-time (06:00 – 18:00 LT), pre-midnight (18:00 – 00:00 LT) or post-midnight (00:00 – 06:00 LT) periods is used to classify them into category A, B and C, respectively. Then the effects of each category of geomagnetic storms on the VTEC were studied.

### 2.2.4 Scintillation analysis

Same as TEC analysis, the data obtained from the SLOG files were sorted in ascending order using the L1 Lock Time and L2 Lock Time columns. All the data with L1 and L2 Lock Times less than 240 seconds were eliminated. The elevation mask angle of 50° was used to avoid the effects of water vapor scattering and multipath effects. RamaRao *et al.* [2006b] have explained that large mask angle reduces the number of satellites available for actual Satellite Based Augmentation Systems operation but gives an opportunity to study the effects of ionospheric irregularities alone on the GPS navigation. Hence, the data with elevation angle greater than 50° were only used. To further remove the glitch, the data were again sorted in descending order using the 60-second Sigma Phase column and the data with unusually large values of 60 second sigma phase were also eliminated to identify the real scintillation events.

Given that the $S_4$ computed by the receiver had the effect of ambient noise and multipath effects which needed to be removed to obtain the true $S_4$ or the final $S_4$. In our case, this is denoted by $S_4 FIN$ and has been computed in order to obtain true scintillations triggered by ionospheric irregularities. Thus, the $S_4 FIN$ (corrected $S_4$) is obtained by differencing the $S_4$ correction from the total $S_4$ in an Random Sum Spectrum (RSS) sense given as

$$S_4 FIN = S_4^2 - S_4 Cor^2$$

(2.5)

Total $S_4$ is dimensionless, therefore, $S_4 FIN$ is also dimensionless. $S_4$ is the logged index by the receiver with noise and $S_4 Cor$ is the correction to $S_4$ at one minute intervals. This was carried out for all the days of 2010. Where the $S_4$ correction was larger than the total $S_4$, the corrected $S_4$ was set to zero (0), since the $S_4$ value then is obviously due to noise.
Chapter 2  Description of Experimental Setup

Though scintillation is known to be basically a night time phenomenon, we have used the data for the whole day to study daytime scintillations also, during low solar activity period. Computed $S_4$ FIN was matched against a standard criteria for scintillation occurrences. Scintillation patches in each hour were manually looked for and recorded with time of occurrence, PRN, and the duration. This was done for each day of 2010. Subsequently, the total occurrence over the whole month and the monthly percentage occurrences were determined.

We have used the occurrence and classification criteria for scintillations used by RamaRao et al. [2006b] and Bhattyacharya et al. [2010] for low latitudes as given in Table 2.2. According to the occurrence criteria, a scintillation event occurred if the $S_4$ index was greater than 0.1 and remained above this benchmark for a minimum duration of three minutes. During the period of scintillation event, the maximum value of $S_4$ reached (even one value), has been used to classify the strength of scintillation as given in Table 2.2. The monthly percentage occurrences were used to study the seasonal occurrence of scintillations on L-band. The seasons are as described in the section 2.2.3.

<table>
<thead>
<tr>
<th>Scintillation Strength</th>
<th>$S_4$ Scale</th>
<th>Corresponding dB Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Weak</td>
<td>$0.17 \leq S_4 &lt; 0.2$</td>
<td>3 - 3.65</td>
</tr>
<tr>
<td>Weak</td>
<td>$0.2 \leq S_4 &lt; 0.3$</td>
<td>3.65 - 6</td>
</tr>
<tr>
<td>Moderate</td>
<td>$0.3 \leq S_4 &lt; 0.45$</td>
<td>6 – 10</td>
</tr>
<tr>
<td>Strong</td>
<td>$0.45 \leq S_4$</td>
<td>&gt; 10</td>
</tr>
</tbody>
</table>

In order to study geomagnetic storm effect on scintillations, the data on SSC and $Dst$ were obtained from the World Data Centers as explained in section 2.2.3 and then the scintillation study for the storm day, one day before and the days after the storm onset was carried out. The storms that occurred in 2011 were also looked for. The same procedures were applied to truncate the data and to study the storm effects on scintillations.
Chapter 3
Vertical Total Electron Content (VTEC) at Suva

This chapter deals with the study of vertical total electron content (VTEC) at Suva using the one year worth of data. The slant total electron content (STEC) values of the ionosphere using GSV 4004B receiver system with its respective angle of elevations were recorded at every one minute interval. The GSV 4004B receiver uses the pseudo-range delays on L1 (1575.42 MHz) and L2 (1227.6 MHz) band signals from GPS satellites to compute the STEC. The STEC values were then converted into VTEC values for uniformity for the elevation angles (≥ 50°) considering ionospheric pierce point at the altitude of 350 km. The day-to-day variability, diurnal, monthly, seasonal and annual variations of VTEC have been presented and discussed.

3.1 Introduction

The TEC is one of the essential and descriptive physical quantities of the ionosphere which has been studied for scientific as well as for satellite applications. For practical (e.g. weather prediction), commercial (e.g. entertainment) and scientific purposes (e.g. ionospheric study) our reliance on trans-ionospheric signals has increased in recent years. The satellites; ATS-3, S-66, INTELSAT, FLEETSAT, etc. have provided great wealth of data both for practical and scientific purposes. The GPS navigation system has been developed to provide all-weather three-dimensional position to the user at any location over land, sea, or air, for both military and civilian users [RamaRao et al., 2006b; 2006c].

The TEC studies commenced with the launch of satellites. The first successful artificial satellite named Sputnik I, launched in 1957, provided the initial useful data on the electron content of the ionosphere and its spatial structure [Davies, 1980]. Later, several satellites including ATS-6, S-66, ETS-2, SIRIO, AE-E and FLEETSAT [Klobuchar et al., 1973] have been launched to study the ionosphere. There have been four geostationary satellites; ATS-1, ATS-3, GOES II and GOES III over the American region extensively used for ionospheric studies [Mercier and Jacobson, 1997].
In 1978 with the launch of Block I GPS satellites, the method of differential group delay technique was developed for ionospheric studies [Klobuchar, 1989]. With the GPS satellites being fully operational by 1995 and the differential group delay technique put into practice, several researchers around the globe studied the TEC of the ionosphere [Mannucci et al., 1993; Wanninger, 1993; Komjathy and Langley, 1996; Davies and Hartman, 1997; Komjathy, 1997; Ciraolo and Spalla, 1998; Warrant and Jodogne, 1998; Davis, 2000; Jakowski et al., 2002; Garner et al., 2008; Bishop et al., 2009]. All these were mainly comparisonal studies whereby GPS-TEC was compared with TEC derived using the theoretical models and other satellites (e.g. GOES II satellite, NNSS and GLONASS). The TEC was also studied using ground based techniques such as low airglow and aurora spectrograph (LORAAS) [Davis, 2000]. It was found that TEC obtained from GPS dual frequency receiver data acquisition and analysis system was in agreement with other methods [e.g. Davies and Hartman, 1997; Komjathy, 1997; Ciraolo and Spalla, 1998; Warrant and Jodogne, 1998; Davis, 2000; Jakowski et al., 2002; Garner et al., 2008] and thus it was realized that GPS could contribute to the global mapping of the TEC as the signals could be received at any part of the Earth.

The diurnal characteristics of TEC are very much dependent on season, solar activity, geomagnetic activity, geographic latitude and longitude. The temporal and spatial TEC variations of the mid-latitude ionosphere are small in comparison to the equatorial and low latitude ionosphere due to the highly dynamic nature of the equatorial ionosphere [Davies, 1980]. This dynamic nature of equatorial and low latitude ionosphere has been of great concern due to large errors encountered in the GPS applications [DasGupta et al., 2007; Bagiya et al., 2009]. The errors are due to the free electrons in the path of the signals, thus the changes in TEC are of concern at the low and equatorial latitudes in order to increase the accuracy of GPS positioning. The studies of TEC variation at different geographical locations and under different geophysical conditions such as geomagnetic storms also need to be carried out.

Apart from these variations, the day-to-day variability in TEC is also of great concern. The day-to-day variability is greater in the equatorial region and at high latitudes and has been attributed to solar, geomagnetic and meteorological factors
The perturbations in the electric field and thermospheric winds can cause fluctuations in the E- and F-layer electron content [Dabas et al., 2006]. Lastovicka [2005] studied meteorological factors and found that processes like planetary waves, gravity waves and tides have direct or indirect effect on the F-region and thus induce variations in TEC. Another prominent feature of low latitude ionosphere is the equatorial electro-jet (EEJ). EEJ is a narrow band of daytime east-ward current flowing in 100-120 km altitude region within ±2° dip equator which has pronounced influence on ionospheric electron content up to the low latitudes [Dabas et al., 2006]. The other phenomenon associated with dynamic nature of the low latitude ionosphere is the equatorial ionization anomaly (EIA). The EIA stimulates a unique latitudinal distribution of ionization with the trough at the magnetic equator and the crests at about 17° on either side of the equator [Ratcliffe, 1972]. This was initially recognized as “Appleton Anomaly” [Galav et al., 2010]. A number of theories have been developed to explain this like the electrodynamic drift theory and diffusion theory, however, they were not enough to explain all the observations [Kumar and Singh, 2009]. According to the electrodynamic drift theory, both the daytime east-west electric field and the north-south geomagnetic field being parallel at the geomagnetic equator, uplifts the plasma. As the plasma rises, it loses momentum and then it diffuses under the effect of gravity along the geomagnetic field lines to the higher latitudes [Balan et al., 2009]. Since the F-region has the highest concentration of electrons, it forms the largest constituent of TEC and thus the formation of anomaly by the variations in electron density is reflected in TEC.

The temporal, seasonal, and solar activity variations of TEC at the low and equatorial latitudes have been studied by many workers using GPS satellites [e.g. Wu et al., 1997; Beach and Kitner, 1999; Thomas et al., 2001; Adewale et al., 2012]. Many studies on the equatorial low latitude ionosphere have been carried out in the Indian region [Kumar and Singh, 2009; Bagiya et al., 2009; Galav et al., 2010; Chauhan and Singh, 2010; Chauhan et al., 2011; SubhadraDevi et al., 2011]. All these studies showed the characteristic features of TEC; a short lived pre-dawn minimum at around 05:00 LT, a steep early morning rise, a mid afternoon maximum at around 14:00 – 15:00 LT, and a steep post-sunset fall. Seasonal variation revealed that TEC is
maximum in the equinoctial months, minimum during winter, and intermediate values during summer.

Under the GPS Aided GEO Augmented Navigation (GAGAN) project, studies on temporal and spatial variations of TEC in the Indian region have been carried out using 18 receivers covering a latitude of 8° to 32° N [RamaRao et al., 2006a; Unnikrishnan and Ravindran, 2010]. They found that the day maximum value of TEC increases from the equator (Trivandrum: 8.47° N, 0° geomagnetic latitude) to the anomaly crest region (Raipur: 21.18° N and Bhopal: 23.28° N) and decreases significantly at the stations outside the anomaly crest region (Dehli: 28.58° N and Shimla: 31.09° N). Thomas et al. [2001] carried out TEC study during 1998-1999 using five GPS receivers in Australia and South East Asia installed at Marak Parak (6.31° N), Malaysia, Pontianak (0.00°), Indonesia, Vanimo (2.4° S), Papua New Guinea, Parepare (3.98° S), Indonesia, and Darwin (12.4° S), Australia. This covered a latitude of up to 35° around geomagnetic equator. They reported that maximum peak of TEC occurred in the anomaly region rather than over the magnetic equator.

In the recent years, a number of studies on TEC have been carried out using the GPS based navigation system at the equatorial to low latitudes, mainly in the American and Indian sectors. With that significant work has not been carried out in the South Pacific region. A dual frequency GPS (GSV 4004B) data acquisition system was established at The University of the South Pacific, Suva, Fiji which has been utilized in this thesis to study the ionospheric TEC variations and scintillations during the low solar activity period 2010. The results on scintillation have been presented in Chapter 4. The STEC data recorded daily by this system were converted to VTEC using the techniques described in Section 2.2.3. First data were converted to MS Excel formats and then processed further using the Matlab codes (Annexure I). The mass plots of VTEC of each month have been generated to illustrate the diurnal variation. The diurnal plots have been used to find monthly means and monthly means were again averaged to obtain the seasonal means of TEC variation.
Chapter 3  Vertical Total Electron Content (VTEC) at Suva

3.2 Results and Discussion

3.2.1 Diurnal variation of VTEC

The diurnal variation of VTEC, in general, at any low latitude ionosphere exhibits a steady increase from the sunrise to the afternoon maximum and then a minimum just before sunrise. Figure 3.1 shows typical variation of TEC at Suva on 23 March 2010. The 23 March was a magnetically quiet day with maximum three hourly $Kp$ value of 0, $\Sigma Kp = -2$ and minimum $Dst$ index value of 2 nT. The VTEC values have been derived from per minute STEC values attained from all the visible satellites and smoothed using the CSAPS toolbox in the Matlab. As mentioned before, only signals with elevation angles greater than 50° have been utilized to obtain TEC from the GPS signals in order to reduce the effects of multipath.

![Figure 3.1: Diurnal variation of VTEC at Suva on 23 March 2010 - a magnetically quiet day ($\Sigma Kp = -2$).](image)

Diurnal variation can be divided into three different sections; a predawn minima, the build-up, the daytime peak/plateau followed by the rapid decay [Bagiya et al., 2009; and Chauhan et al., 2011]. The VTEC at Suva shows these characteristics of a low latitude ionosphere with a short lived pre-dawn minimum between 02:00-06:00 LT (LT = UT + 12 hrs), with a gradual increase with time of the day followed by a broad mid-afternoon maximum around 14:00-1500 LT and a steep afternoon to post-sunset fall.
The peak of the diurnal maxima at low latitude is very much dependent on the strength of the equatorial ionization anomaly (EIA).

The mass plots of daily diurnal variations for all the months of 2010 are shown in Figures 3.2a and 3.2b. These mass plots show the typical diurnal pattern with significant day-to-day variability. The diurnal peak VTEC has been observed to vary from day-to-day and month to month. In general, the diurnal peak VTEC is found between 12:00 - 15:00 LT ranging from 70 to 100 TECU. The large variation in the daytime is evident, however, the nighttime variation is found to be less and almost constant for all the months.

In order to investigate the day-to-day variability, the percentage standard deviations about the mean for each month were calculated. The variance and standard deviations are used to study the variability. In this case the standard deviation (SD) has been used, which is the square root of variance. The variability discussed here are the percentage of SD with respect to mean. The variability was calculated specifically at 05:00 LT, 14:00 LT and 22:00 LT to represent the variability in the post-midnight, daytime and pre-midnight periods as shown in Table 3.1.

Table 3.1: Mean VTEC and the variability during post-midnight, daytime and pre-midnight periods for each month of 2010.

<table>
<thead>
<tr>
<th>Months</th>
<th>Post-midnight</th>
<th>Daytime</th>
<th>Pre-midnight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Variability (%)</td>
<td>Mean (TECU)</td>
<td>Variability (%)</td>
</tr>
<tr>
<td>January</td>
<td>9.0</td>
<td>65</td>
<td>12.5</td>
</tr>
<tr>
<td>February</td>
<td>7.6</td>
<td>65</td>
<td>14.4</td>
</tr>
<tr>
<td>March</td>
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Figure 3.2 (a): Mass plots of monthly diurnal variation of VTEC at Suva from January to June 2010. Thick red line shows the monthly TEC average.
Figure 3.2 (b): Mass plots of monthly diurnal variation of VTEC at Suva from July to December 2010. Thick red line shows the monthly TEC average.
Thus, the overall variability of TEC during daytime was 13.5% from the mean of 80 TECU, the pre-midnight variability is 7.2% from the mean of 63 TECU and the post-midnight variability was 6.5% from the mean of 65 TECU.

With the aim of studying the pure quiet day variability, the Q-days VTEC for each season have been plotted as shown in Figure 3.3a and 3.3b. In the hot and wet season, the VTEC in post-midnight period varied between 62 and 72 TECU, the daytime VTEC varied between 72 and 97 TECU and the pre-midnight VTEC varied between 62 and 73 TECU showing a variation of 10 TECU, 25 TECU and 11 TECU, respectively. During the cold and dry season, the post-midnight VTEC between 62 and 73 TECU, the daytime VTEC between 70 and 87 TECU and the pre-midnight VTEC varied between 64 and 73 TECU showing a variation of 11 TECU, 18 TECU and 9 TECU in the respective their periods. This shows that daytime TEC variation is considerably higher during both the seasons as compared to the pre-midnight and post-midnight periods which show almost same variability. It can be clearly seen from Figures 3.3a and 3.3b that, in general, the day-to-day variability is larger in the hot and wet season as compared to cold and dry season.

Rishbeth and Mendillo [2001] studied electron content of F2-layer at 13 stations, grouped into sub-auroral stations (magnetic latitudes: 48°-58° N/S), intermediate stations (magnetic latitudes: 37°-42° N/S) and low latitude stations (below 12°) for 34 years from 1957 to 1990. They found that from the average at all the 13 stations, the variability is higher in the nighttime (SD = 33%) than in the daytime (SD = 20%) and is higher during equinox than during solstice. Latitudinally, they found least variability at intermediate latitudes. At the three equatorial stations; Djibouti (11° N), Huancayo (12° S), and Vanimo (3° S), they found the daytime variability to be 17%, 19% and 17%, respectively, while nighttime variability was 28%, 29% and 40%, respectively. Thus low latitude daytime variability is smaller than the mid-latitude stations, while nighttime variability is higher than at mid-latitudes and no consistent seasonal pattern is visible.
Figure 3.3a: Hot and Wet season quiet day variations of VTEC during 2010.

Figure 3.3b: Cold and Dry season quiet day variations of VTEC during 2010.
Chandra et al. [2009] studied the day-to-day variability in critical frequency of F-layer ($f_0F_2$) using data collected at Ahmedabad during 1969 as a proxy for TEC and found that nighttime variation (SD up to ± 40%) was greater than daytime (SD up to ± 20%) and seasonally daytime deviations were of the same order, while nighttime deviations were less during equinoxes. However, in our case the daytime variability is higher compared to the nighttime variability. This is consistent with the results from the Indian low latitude region [e.g. Bagiya et al., 2009 (Rajkot- 22.29° N); Chauhan et al., 2011 (Agra- 27.12° N); Kumar and Singh, 2009 (Varanasi- 25.28° N); Dabas et al., 2006 (Dehli- 28.6° N)] who found daytime variability to be higher than the nighttime period.

Rishbeth and Mendillo [2001] from their studies concluded that geomagnetic activity is a major cause of day-to-day variability at mid and low latitude stations, since their findings revealed greater variability during night. At nighttime, the electron density is low and there is lack of photochemical control, therefore, the auroral sources of magnetic activity have dominant role on the TEC variation at night. Though Chandra et al. [2009] found similar results to Rishbeth and Mendillo (as stated above), they attributed their findings to the variability in the thermospheric neutral temperature and winds at low latitudes.

The day-to-day variability in TEC is still a complicated topic in ionospheric physics which needs further investigations. The ionosphere is located at a transition region where it has influence of solar wind dynamic pressure from top and influence of the lower atmospheric waves originating from the bottom, therefore, understanding and modeling the day-to-day variability are highly complicated [e.g. Rishbeth and Mendillo, 2001]. As discussed earlier VTEC is the total number of free electrons in the path of signals from the satellite to the receiver, therefore, VTEC covers all the regions of the ionosphere; D-, E- and the F-regions as well as the plasmasphere. The plasmaspheric contribution to TEC is almost insignificant [Bishop et al., 2009], however, any turbulence in the D-, E- or F-region would affect the overall VTEC. The day-to-day variability is contributed by the various parameters like EUV flux, geomagnetic activity, equatorial Electrojet strength and local temporal conditions in the thermosphere [Dabas et al., 2006]. Recently, other very important factors have been
found that brings about day-to-day variability in TEC. These include; variation in thermospheric neutral composition, variation in neutral winds, influence of solar dynamic processes, atmosphere-ionosphere coupling, changes in solar flux, vertical coupling resulting from atmospheric waves like gravity waves and tides or planetary waves, the equatorial electrojet (EEJ) generated by atmospheric tides and the sudden stratospheric warming events [Sripathi and Bhattacharyya, 2012].

All the regions of the ionosphere are responsible for the day-to-day VTEC variability observed at any station. Firstly, the E-region electrodynamics. The E-region plays a critical role in the electrodynamics of the ionosphere since it has high electrical conductivity compared to the other regions. The conductivity of the E-region and its horizontal, vertical and temporal coupling leads to the formation of EEJ [Nicholls et al., 2012]. The existence of multiple neutral species with different ionization rates makes it complicated to model the ionization and photochemical processes. Nicholls et al. [2012] found that fractional TEC variation at low latitudes is around 15-20% with fractional peak variability of E-region electron density ($N_mE$) at low latitude at noon of about 15-17% while nighttime variability is much larger (~50-100%). The dynamics of the neutral wind and the EEJ strength also brings about the variability in TEC [RamaRao et al., 2006a]. Any disturbance in electric fields and neutral winds affects the equatorial plasma fountain and plasma transport that results in pole-ward extension or equatorward contraction of the EIA crests and changes of the ionospheric layer heights [Lin et al., 2009]. The neutral winds are driven by external sources usually attributed to the Joule heating and largely depend upon the distribution of the energy sources in altitude, latitude and longitude [Heelis, 2004]. Maute et al. [2012] used NCAR TIME-GCM model to simulate and investigate the factors affecting the $E\times B$ drift and found that neutral winds at all latitudes are the main contributor to $E\times B$ drift. During the nighttime, the winds in the F-region are more important since the conductivity is very low at night. During the daytime, neutral winds in the lower E-region (below 200 km) are more important. As the strength of $E\times B$ drift changes, there is rapid movement of plasma from the equatorial region which gets transported towards the poles or vice versa. They also found that gravity and plasma pressure driven current, the geomagnetic main field and the longitudinal variation in E-region conductivity could also affect the
The $\mathbf{E} \times \mathbf{B}$ drift is also dependent on the equatorial electrodynamics modulated by EEJ and counter electrojet events (CEJ) [Hajra et al., 2012]. At times the EEJ current reverses from eastward to westward during morning and afternoon hours and even on magnetically quiet days and is known as CEJ. An enhanced ionospheric E-region current flowing at 100 km altitude in the narrow latitude belt (~ 5° dip width) around the dip equator is referred to as EEJ. The EEJ is produced by the daytime dynamo electric field in the presence of the horizontal magnetic field at the dip equator. A good correspondence is noted between EEJ strength and daytime $\mathbf{E} \times \mathbf{B}$ plasma drift at magnetic equator [Hajra et al., 2012]. On CEJ days, weakening or disappearance of fountain effect leading to perturbations in EIA has been reported. Sripathi and Bhattacharyya [2012] asserted that EEJ is generated by atmospheric tides through dynamo action, therefore, any modulation of E-region winds by planetary waves would produce oscillations in EEJ and subsequently the strength of EIA. Dabas et al. [2006] studied F-region variability at Thiruvanthapuram (8.5° N), Kodaikanal (10.2° N) and Delhi (28.6° N) during 1970 and 2001, a high solar activity period and found that variations in daytime $f_0F_2$ were not related to solar and magnetic activity changes, but were controlled by EEJ strength variations and they considered the perturbations in electric fields and thermospheric winds as the main cause of day-to-day variability, since these produce fluctuations in the E- and F-layers. Chandra et al. [2009] reckoned that fluctuations in plasma density arise due to the plasma instabilities that operate in the electrojet region like the two-stream instability and the cross-field instability mechanisms. Tides or Planetary waves could also induce TEC variations. At low latitudes a large-scale 24-h variation called the diurnal tide dominates the neutral atmosphere motion [Heelis, 2004]. In E-region, the total ion concentration is in photochemical equilibrium and has local time distribution so, any disturbance would affect the overall TEC. Sripathi and Bhattacharyya [2012] deemed that the efficiency of planetary waves increases in perturbing E-region drifts, electric fields and GPS-TEC at EIA due to modulation of E-region dynamo, during the low solar activity period. Meanwhile, a change in the neutral composition can also result in either increase or decrease in TEC since neutral composition modifies the photochemistry of the ionosphere [Lin et al., 2009]. Chauhan et al. [2011] also explained day-to-day
variability in TEC as due to variations in thermospheric composition both during day and nighttime. They justified that as the temperature in the thermosphere decreases in the nighttime, the electron contents in the field tubes lessens rapidly after sunset, since the total magnetic field tube is very small at the equatorial and low latitudes. Subsequently, at sunrise the magnetic field tubes fill up rapidly because of their low volume resulting in steep increase in ionization. The solar dynamic processes could also alter the TEC since photoionization rate is affected. Sripathi and Bhattacharyya [2012] found significant oscillation in TEC with a period of 25-30 days which they associated with the phenomenon of geomagnetic activity recurrence due to solar wind high speed streams coming from coronal holes during the declining phase of a solar cycle or the 27 day period in solar EUV flux. However, Dabas et al. [2006] found that short and long term variations in the daytime electron content were not related to the solar and magnetic activity changes most of the time which again require more intense study. Another reason for TEC variability could be variations in solar flux. Some researchers [e.g. RamaRao et al., 2006a; Bagiya et al., 2009; Chauhan et al., 2011; Adewale et al., 2012] have related the day-to-day variability in TEC to changes in solar flux (i.e. changes in the activity of the Sun). Galav et al. [2010] found the correlation between solar flux and the daytime ionospheric electron content to be 0.74, which clearly implied that solar flux is the single most dominant factor attributing to the observed diurnal variations. They also found the zenith angles at which the radiation impinges the Earth’s atmosphere as an important contributor to the diurnal variation.

Maute et al. [2012] using NCAR TIME-GCM model suggested that the upward $\mathbf{E} \times \mathbf{B}$ drift decreases with decreasing solar flux since the neutral winds with respect to altitude depend on the solar activity. Variations in TEC could also result from atmosphere-ionosphere coupling effects. There is either direct (e.g. vertical propagation of planetary waves - PW) or indirect (e.g. through the E-region dynamo) atmospheric-ionospheric coupling at equatorial and low latitudes [Chau et al., 2012]. Since the quasi-stationary PWs are limited to high and middle latitudes it is difficult to conceive, however, a number of researchers have studied the indirect coupling through the E-region dynamo in order to explain the daytime variability [e.g. Chandra et al., 2009; Sripathi and Bhattacharyya, 2012; Chau et al., 2012]. Lately, studies have shown that
sudden stratospheric warming (SSW) events could also bring about changes in TEC. During SSW events the stratospheric temperature abruptly increases by tens of degrees, the normal winter polar vortex changes its shape and position and zonal mean winds become weaker or even changes direction [Chau et al., 2012]. As a result, planetary waves are generated in the troposphere which propagate upwards and finally, the westward momentum gets deposited that slows down or reverses the stratospheric winter jet. Sripathi and Bhattacharyya [2012] found that large-scale wave like structures in the EEJ strength during SSW events could cause fluctuations in the GPS-TEC. Chau et al. [2012] presented in their review that there was a large increase in TEC (up to 150%) in the morning sector during a SSW event on 27 January 2009 recorded at Jicamarca. The post-midnight time variability could also be due to field aligned irregularities. Nishioka et al. [2012] studied field aligned irregularities at Kototabang (0.2° S), Indonesia, and found that the post-midnight field aligned irregularities are induced by uplifting of the F-layer which occurs around midnight and this phenomenon could also bring about post-midnight variability in TEC.

Our results show large variability in the daytime GPS TEC as compared to the nighttime period at Suva. Thus, from above a number of factors affect day-to-day variability. During quiet time the equatorial $\mathbf{E} \times \mathbf{B}$ drifts are driven by neutral wind generated E-region dynamo electric fields and by the F-region polarization electric fields. With that, changes in global tides, planetary and gravity waves, induce high variability in the thermospheric winds and thus variations in TEC. Seasonally, the variability is larger during hot and wet season as compared to cold and dry season which could be due to $\mathbf{E} \times \mathbf{B}$ drift modulated by EEJ and CEJ.

### 3.2.2 Monthly VTEC variation

The contour plot of monthly averages of TEC during 2010 is shown in Figure 3.3. This shows a clearer picture of the differences in VTEC with the months. The diurnal peak has maximum TEC in December followed by February, at around 14:00 LT whereas, the lowest values of TEC occur in June and July. This implies the VTEC is high in the beginning from the months of January and gradually decreases as we...
proceed to the middle of the year. After reaching the minimum during the middle of the year (June) it increases slightly in July and shows another minimum in August, it then progressively increases and attains a maximum values in December.

Wu et al. [1997] studied TEC in China covering the latitudes from 21.9°-26.2° N and found maximum TEC in April and minimum in July. Kumar and Singh [2009] studied TEC variation at Varanasi (25.28° N), India, during 2007-2008, a low solar activity period and found maximum TEC in October and April, while minimum in December and July. Chauhan et al. [2011] from TEC study at Agra (27.12° N), India, during 2006 to 2009 and found that during equinoctial months of March, April, September and October had highest values of TEC, followed by summer months of May, June, July and August, while lowest TEC values were attained in the winter months of November, December, January and February. RamaRao et al. [2006a] under
the GAGAN project during 2004-2005 found highest day maximum during September and October at Raipur (21.18° N) and Hyderabad (17.44° N) while at Dehli (28.6° N) a reduced diurnal maximum occurred during these months.

At Suva, being situated at the trough of EIA and in the Southern hemisphere, the month of December receives the most sunlight while June and July receive the least. It is well known that ionosphere plasma density is determined mainly by solar photoionization [Unnikrishnan and Ravindran, 2010], as the amount of solar radiation changes the diurnal maxima also changes throughout the year. The changes in the intensity of the incoming radiation and the zenith angle at which it incidents on the Earth’s atmosphere could also bring about changes in the monthly TEC. In addition, the $E \times B$ drift brings plasma from lower to higher altitudes during daytime and vice versa during nighttime. The rising plasma reaches the high altitudes until it loses momentum and diffuses along the magnetic field lines to higher latitudes due to effects of gravity and pressure gradient forces resulting in the formation of crests in electron density on either side of the magnetic equator. The monthly variations indicate the role played by the EEJ strength at equatorial and low latitudes. The strength of EEJ is found to intensify during the equinoctial months (October and April) [RamaRao et al., 2006a]. Dabas et al. [2003] found the correlation between $E \times B$ drift and EEJ to be 0.85 with the data recorded at Trivandrum (8.5° N; geomagnetic latitude: 0.3° N) and Alibag (18.6° N; geomagnetic latitude: 13.4° N), India, implying that any change in EEJ will affect the $E \times B$ drift. With that $E \times B$ drift displays seasonal variability [Rabiu et al., 2007]. During equinoctial months, the sub-polar point is around the equator, where the eastward electrojet associated electric field is often largest. Therefore, due to the combined effect of photoelectron abundance and the most intense eastward electric field regions, the fountain effect is most developed during equinox. While, during the solstice (winter and summer) months, photoelectrons at the equator decreases because the sub-polar point moves to higher latitudes and the fountain effect is decreased [Kumar and Singh, 2009]. Due to Suva being located at the trough of EIA, the maximum in VTEC occurred in hot and wet months of January and December whereas, minima in cold and dry months of May and August. Thus, VTEC at Suva seems to be primarily controlled by solar radiation intensity which is larger during hot and wet season as compared to
cold and dry season. In addition, the fountain effect could also bring about seasonal differences in VTEC. During the hot and wet season, the sub-polar point is below the equator and in the southern hemisphere, where the eastward electrojet associated electric field would be largest. Therefore, due to both abundance of photoelectron and the most intense eastward electric field regions, the fountain effect would be most developed in hot and wet season as compared to cold and dry season, when the sub-polar point is in the northern hemisphere.

### 3.2.3 Seasonal VTEC variation

The area between Tropic of Cancer (23.5° N) and the Tropic of Capricorn (23.5° S) do not actually have the four seasons weather pattern, as it receives large amount of solar radiation throughout the year. Fiji is located in the Southern hemisphere, between the equator and the Tropic of Capricorn (23.5° S) and exhibits only two seasons called: Hot and Wet and Cold and Dry [Kumar, 2003]. The Hot and Wet season includes the months of January, February, March, April, November and December while the Cold and Dry season includes May, June, July, August, September and October. Our measurement site Suva (18.15° S, 178.45° E) lies well within the Equatorial Ionization Anomaly. To study seasonal TEC variations, the months were sorted according to the seasons they fall into and the monthly VTEC means were again averaged to obtain the seasonal VTEC variation. Figure 3.5a and 3.5b shows the diurnal variations of VTEC during the two local seasons during 2010.

The monthly average plots in Figures 3.5a and 3.5b show that TEC values are high in the hot and wet months as compared to the TEC values in cold and dry months by about 12 TECU from the mean. In cold and dry months, the peak diurnal VTEC for all the months has a maximum of 79 TECU in October and a minimum of 72 TECU in June. There is also an apparent diurnal plateau for all the months in this season. Whereas in hot and wet months, the peak diurnal VTEC shows highest value of 93 TECU in December and lowest in April with 79 TECU.
Figure 3.5(a): Average monthly variations of VTEC during cold and dry season during 2010 at Suva.

Figure 3.5(b): Average monthly variations of VTEC during hot and wet season during 2010 at Suva.
As the seasonal average is computed from the monthly averages, the difference becomes explicit as given in Figure 3.6. The seasonal averages show a very short lived minima at 05:00 LT. However, there is a significant difference in the daytime VTEC of about 15 TECU in the two seasons. With cold and dry seasonal average, there is a diurnal plateau from 09:00 to 16:30 LT in the range of 72 – 75 TECU whereas in hot and wet season, there is no significant plateau, but a distinct crest of 86.5 TECU at around 14:45 LT is evident. The annual VTEC (seasonal average) displays the same minima at 05:00 LT with a crest of 81 TECU at 14:00 LT.

![Figure 3.6: Seasonal and Annual average variations of VTEC during 2010.](image)

Our results are in agreement with the results presented for Southern Hemisphere Anomaly region; Presidente Prudente, Brazil (22.1° S) by da Costa et al. [2004] and by Tsai et al. [2001] at YMSM (25.2° N) and DGAR (7.3° S) stations in Taiwan. Tsai et al. [2001] found during 1997, the TEC values at northern crests were higher in winter than in summer but the TEC values at southern crests were higher in summer than in winter. da Costa et al. [2004] found maximum TEC in summer (December) and minimum in winter (June) and the largest diurnal plateau in autumn equinox (March). A
number of studies in the Northern anomaly region have been carried out especially in the Indian EIA region. RamaRao et al. [2006a] under the GAGAN project during 2004-2005 found highest day maximum values of VTEC during equinox at Raipur (21.18° N) and Hyderabad (17.44° N) and a reduced diurnal maximum at Dehli (28.6° N). Kumar and Singh [2009] studied TEC variation at Varanasi (25.28° N), India, during 2007-2008 and found maximum TEC in equinox and minimum in winter. Bagiya et al. [2009] studied TEC at Rajkot (22.29° N), India, during 2005-2007 and found maximum TEC during equinoctial months and minimum during winter months and intermediate values during summer months. Galav et al. [2010] from a study on GPS-TEC at Udaipur (24.6° N), India, during 2005-2008 reported that peak TEC is maximum in spring and minima in winter. Chauhan and Singh [2010] studied TEC variations at Agra (27.17° N), India, during January to December 2007 and found maximum TEC values in equinox and summer and the minimum values in winter. Chauhan et al. [2011] from monthly TEC variation at Agra (27.12° N), India, during 2006 to 2009 reported maximum TEC in the equinoctial months less in summer months and least in winter. Wu et al. [1997] studied TEC in China covering the latitudes from 21.9°-26.2° N and found that seasonally, maximum TEC occurred in equinoxes while minimum in winter and summer.

In Southern Hemisphere, December falls in the summer solstice. During this time of the year the Sun rays are perpendicular to the Tropic of Capricorn which means the sub-polar point is in the Tropic of Capricorn and Fiji is just near to it, thus receives the highest level of solar flux, generating maximum VTEC in December. June falls in winter solstice when the Sun rays are perpendicular to the Tropic of Cancer (the sub-polar point is in the Tropic of Cancer), therefore, the rays are slant to Tropic of Capricorn generating lowest VTEC. Thus, in June solar flux reaching the Southern Hemisphere Anomaly ionosphere is at minimum. The month of September falls in the vernal equinox when the Sun rays are perpendicular to the equator (the sub-polar point is at the Equator) and thus the entire Earth receives 12 hours of daylight which could contribute to the formation of the largest diurnal plateau between 08:00 till 18:00 LT as shown in Figure 3.5a. On the other hand, the autumnal equinox of March has the formation of the crest at 12:00 LT. Changes in the ratio of atomic oxygen and molecular
nitrogen [O/N₂] in the F-region could bring about seasonal changes since the [O/N₂] ratio is larger in summer compared to winter [Chauhan et al., 2011]. This could result in high electron loss rate in winter than in summer. Based on calculations of scale height of the solar radiation absorbing gas, Bagiya et al. [2009] suggested that in equinoctial months the solar radiation is absorbed mainly by atomic oxygen. This could be the reason for largest diurnal plateau of TEC in the September (equinox). The lowest values of TEC observed in the Northern hemisphere were in winter months [RamaRao et al., 2006a; Bagiya et al., 2009; Chauhan et al., 2011], consequently, lowest TEC in the Southern hemisphere would also be in the winter months which corresponds to the cold and dry season in our case.

In addition to the dependence on the production and loss of ionization, the seasonal variations of VTEC also depend on the transport of plasma through winds and hence changes in thermospheric neutral composition. This transequatorial wind is induced by solar heating and moves from summer to winter hemisphere which implies that during summer the meridional winds are equator-ward. This equator-ward wind pushes the plasma along the geomagnetic field lines to higher altitudes where the production and loss ratio of electrons is high. This behavior increases the electron density at the low latitudes. However, during winter the meridional winds are pole-ward. This pole-ward wind then pushes the plasma to lower altitudes where production and loss ratio of electrons is reasonably low. This phenomenon decreases the electron density in winter months in northern hemisphere [Bagiya et al., 2009]. Another model developed by Millward et al. [1996] called the Coupled Thermosphere Ionosphere Plasmasphere (CTIP) model and later modified to Coupled Thermosphere Ionosphere Plasmasphere Electrodynamics (CTIPE) by Fuller-Rowell et al. [2002] gives that magnetospheric processes deposits large amounts of energy into the thermosphere/ionosphere at high latitudes causing Joule heating. This drives a local equator-ward wind on the equator-ward side of the auroral region. In winter hemisphere, this equator-ward wind is then in the opposite direction to the existing pole-ward wind produced by solar heating. So, in the summer northern hemisphere, the transequatorial wind suppresses the development of the northern equatorial anomaly region and enhances the other side. On the other hand, auroral equator-ward wind goes
north so that TEC maintains in the southern equatorial anomaly region and the south crest moves equator-ward [Tsai et al., 2001]. In our case during the cold and dry season (winter) the overall VTEC is suppressed while in hot and wet season (summer) the VTEC is increased. This implies that the crest is more developed during hot and wet season and could be the result of an increase of photoionization during this time and the the effect of the winds. During hot and wet season, the transequatorial wind is directed north-ward which drives the plasma to higher altitudes. With that, the equator-ward wind is also in the same direction and pushes the plasma further to higher altitude whereby the production and loss ratio of electrons is high. Thus, an enhancement in TEC is seen. While in cold and dry season, the photoionization decreases and the transequatorial and equator-ward winds are in opposite directions. The transequatorial wind is south-ward, while the equator-ward wind is north-ward. The pole-ward transequatorial wind drives the plasma to lower latitudes where the production and loss ratio of electrons is low, while the equator-ward wind tries to push it up. These opposing winds offsets each other and as a result a reduction in TEC is recorded.

3.3 Conclusions

The main features of diurnal, day-to-day, monthly and seasonal variations of VTEC studied at Suva can be concluded as follows:

- Diurnal variation shows a short lived minima in TEC at around 02:00-06:00 LT then a gradual rise with an afternoon peak TEC at around 14:00 LT followed by a quick decay until sunset.
- The day-to-day variability in TEC is larger in the daytime with peak at around 11:00-15:00 LT as compared to the pre- and post-midnight variabilities. There is no significant difference in VTEC variability in the pre-midnight and post-midnight periods. Seasonal day-to-day variability is more in hot and wet season as compared to cold and dry season.
- The monthly variation exhibited a longer plateau in September and a maximum in December (summer solstice) while the minima in June (winter solstice).
- Seasonal variation revealed that during hot and wet season, the TEC values are higher when compared to the cold and dry season. The average VTEC in cold and dry shows a diurnal plateau between 09:00 to 16:30 LT in the range of 72 – 75 TECU whereas the hot and wet season exhibits no plateau but a distinct crest of 86.5 TECU at around 14:45 LT.
- The annual average of TEC for 2010 showed an apparent minima before sunset at around 05:00 LT and a peak at 14:00 LT with a decrease in TEC from afternoon to nighttime which is almost a typical diurnal variation.
Chapter 4
GPS L-band Scintillation Activity at Suva

This chapter examines the monthly and seasonal occurrences of amplitude scintillations on GPS L-band (1575.42 MHz) signal recorded during one year period. The GSV 4004B GISTM data acquisition system computes total scintillation index $S_4$ of amplitude scintillations over the 60-second intervals. This total $S_4$ also includes the effects of ambient noise and the multipath propagation of signals. The GSV 4004B data acquisition and recording system is also able to compute the correction to the total $S_4$, due to ambient noise, based upon the average of the raw 1-Hz C/No values over the same 60-second intervals. The final $S_4$ was computed by differencing the $S_4$ correction from the total $S_4$ in an Random Sum Spectrum (RSS) sense given by equation 2.5 in section 2.2.4. The final $S_4$ has been used to categorize scintillations into weak ($0.2 \leq S_4 < 0.3$), moderate ($0.3 \leq S_4 < 0.45$) and strong ($0.45 \leq S_4$) scintillation activities. The percentage monthly and seasonal occurrences of different categories of scintillations have been presented.

4.1 Introduction

Scintillation measurements have been used as the key diagnostic tool for detecting the irregularities in electron density in the E- and F-region of ionosphere. The knowledge of scintillation activity is not only important to determine the spatial and temporal distribution of the irregularities but also to understand the physical processes that lead to the formation of such irregularities [Basu and Basu, 1989]. Due to these irregularities the ionosphere becomes very turbulent and upon passing through these irregularities the radio waves can suffer random phase and amplitude fluctuations. Ionospheric scintillation is defined as the fluctuation in the intensity of signal as it traverses through the irregularities in the ionosphere [Basu and Basu, 1989]. The stronger the scintillation, the greater is the impact on the communication and navigation systems [Hanslmeier, 2004].

The earliest analyses of amplitude scintillations were carried out by recording radio waves from radio stars to gather information about the sizes, shapes and motions
Chapter 4  GPS L-band Scintillation Activity at Suva

of irregularities [Bartusek and Felgate, 1966; Crane, 1974]. The advent of artificial satellites provided the opportunity of recording the satellite beacon signals in 1960s with the operation of ATS-3 satellite and ATS-6 satellite in 1966. The L-band scintillation analysis pioneered after the launch of P76-5 satellite in May 1976. The satellite transmitted VHF, UHF and L-band signals which were recorded at ground stations; Poker Flat (Alaska), Ancon (Peru), Kwajalein (Marshall Islands), and Stanford (California). The study on P76-5 satellite signals by Fremouw et al. [1978] revealed that at all the bands, only equatorial stations observed scintillations which were present during both night and day times. Based on amplitude scintillations at 1.5 GHz from MARISAT satellite signal recorded at Huancayo (12° S) and Ascension Island (7.4° S) during 1979-1986, Basu et al. [1988] reported that seasonal occurrence showed clear equinoctial peaks during low solar activity and vernal equinoctial peaks during high solar activity with that, equatorial scintillations were more pronounced in the pre-midnight between 22:00-00:00 LT.

With the launch of the Block I GPS satellites in 1978, a large scale scientific research using the GPS, on the ionosphere, initiated in 1981 at Ascension Island, in the Atlantic Ocean near the equator with a joint effort between the Air Force Geophysics Lab (AFGL) and Stanford Geophysics Research Lab [Coco, 1991]. Klobuchar [1991] summed up all the previous findings stating that the region of strongest scintillations lies approximately ±30° on either side of the Earth’s geomagnetic equator. Strong equatorial scintillation fading can last for several hours in the pre-midnight initiated after local sunset till midnight. Seasonal analysis revealed that from April through August the scintillation activity is generally weak in the American, African and Indian longitudes [Klobuchar, 1991; Basu et al., 1988]. In the Pacific region, however, scintillation occurrence is maximum in the April-August months and minimum in the September-March months, as shown in this thesis work. The daytime scintillations has been associated with the equatorial sporadic-E (Esq) [Rastogi, 1972], while the nighttime scintillations are due to plasma bubbles. The generalized Rayleigh-Taylor (GRT) instabilities is the physical mechanism for the generation and growth of the plasma bubbles which then rises to higher altitudes. Subsequently, due to non-linear
evolution of the $\mathbf{E} \times \mathbf{B}$ drift, these bubbles then travels to higher latitudes [Guzdar et al., 1981].

Though, through technological advancements, the GPS has improved the navigation systems, the knowledge on the morphology of scintillation in the anomaly region is still not fully understood and prompted many workers to study this phenomenon from different parts of the globe under various geophysical conditions [e.g. Basu and Basu, 1989; Aarons et al., 1997; Beach and Kitner, 1999; Du et al., 2000; Datta-Barua et al., 2003; Groves, 2004; Van-Dierendonck and Rastburg, 2005; Ramarao et al., 2006b; Spogli et al., 2009; Zou and Wang, 2009; Bhatyacharya et al., 2010; Prikryl et al., 2011; Adewale et al., 2012]. The advent of desktop computers and other technological gadgets has enabled researchers to process the signals with ease and obtain the full range of statistical parameters like $S_4$ index, $S_4$ due to noise, C/No and scintillation spectrum (in some cases), on a real-time basis.

The studies on temporal and seasonal variations of scintillations have been done using the signals from GPS satellites by several workers; Thomas et al. [2001] (Australia and South East Asia) found that between 06:00 to 20:00 LT no scintillation was recorded during 1998-1999 at Vanimo (2.4° S), Papua New Guinea. The scintillations commenced around 20:00 LT, about 2 hours after local sunset and could last till local midnight; Datta-Barua et al. [2003] (Rio de Janeiro, Brazil- 22.9° S) found that scintillations were present on almost all the nights between 00:00 - 06:00 UT (21:00 – 03:00 LT); RamaRao et al. [2005] (Waltair, India) and RamaRao et al. [2006a] (under the GAGAN a network in India covering the geographic latitude of 8° to 32° N) found maximum scintillation occurrence during post-sunset to midnight (19:00 – 00:00 LT) with peak at around 21:00 LT during equinox (March, April, September and October), moderate occurrence during winter (November, December, January, February) and low occurrence during summer solstice months (May, June, July and August); DasGupta, [2006] (Calcutta, India- 22.58° N) found that scintillations at L-band mostly occurred between local sunset and midnight with a maximum between 19:00 to 20:00 LT. The seasonal analysis showed that maxima occurred in the equinox; RamaRao et al. [2006c] (Waltair, India) found that percentage occurrence of scintillations at 1.5 GHz (L-band) is higher in the pre-midnight period with a maximum
around 21:00 LT. Seasonally, the percentage occurrence of scintillation is higher during equinox (highest in vernal equinox than in winter equinox), low during winter and almost no scintillations during the summer months; Kitner et al. [2007] (Brazil, low latitude region) found that scintillations usually occurred between 2100-0300 LT, i.e. post-sunset to dawn period; Muella et al. [2008] (seven stations in the Brazilian low latitude region) observed that the strong scintillations were predominant in the pre-midnight hours; However, Zou and Wang [2009] (Guilin, China- 25.29° N) found that amplitude scintillations rarely occurred in the nighttime (18:00 – 06:00 LT) during the two years (2007-2008) of their study during the low solar activity period. They observed only three events of nighttime scintillations with $S_4 > 0.2$ while the strong amplitude scintillations ($S_4 > 0.4$) were observed in the daytime (06:00-18:00 LT); Bhattyacharya et al. [2010] at Bhopal (23.2° N, under the Indian EIA) found maximum scintillation occurrence in March and January months, while minimum in November and May months. The nocturnal variations in each season revealed that in the equinoctial and winter months, scintillation occurrence was maximum in the pre-midnight period and minimum in the post-midnight period whereas during summer months scintillation occurrence was maximum in the post-midnight period and minimum in the pre-midnight period; Manju et al. [2011] using the data recorded at Trivandrum (8.5° N), Hyderabad (17° N) and Bhopal (23° N), India, during 2005-2005, a low solar activity period, found that scintillations were more frequent in equinox than in solstice months. They also found that scintillations were associated with equatorial spread-F (ESF) events with duration greater than 150 minutes, during equinoctial months. Based on scintillation analysis at Lagos (6.5° N), Nigeria, during February to August 2010, Adewale et al. [2012] reported that amplitude scintillations not only occurred in the nighttime but also occurred in the daytime of all the months. Their study also showed that the $S_4$ increased during post-sunset hours reaching maximum of 0.7 in some cases, however, daytime amplitude scintillations with $S_4 > 0.4$ were rarely observed. They also found that nighttime amplitude scintillations were accompanied by phase scintillations and VTEC fluctuations and the VTEC depletions between 21:00 and 00:00 LT produced both amplitude and phase scintillations; Paznukhov et al. [2012] using the scintillation data at Cape Verde (16.7° N), South Africa, Lagos (6.5° N),
Nigeria and Kampala (0.3° N), Uganda, recorded during 2010 reported that overall the GPS scintillations during 2010 were weak, and scintillations with $S_4$ greater than 0.25 were rarely observed and scintillations were predominantly observed during the equinoctial months. There is only one study by Kumar et al. [2007] in the South Pacific region, on SHF scintillations at Suva (18.08° S), Fiji, recorded during December 2003 to June 2004 at 3.925 GHz (C-band) signals from Intelsat 701 satellite which reported that scintillations were, in general, sparse with maximum occurrence in the daytime (83.4%), less in the pre-midnight (9.7%) and least in the post-midnight (6.8%) hours with scintillation patches of duration of about 2 minutes present in all the three time categories. The patches of durations $\geq$ 10 minutes were very rarely observed.

Studies from several researchers [e.g. Thomas et al., 2001; Valladares et al., 2004; RamaRao et al., 2006a; Muella et al., 2008; Paznukhov et al., 2012] on latitudinal variation of scintillations showed that scintillation activity was greater in the anomaly crest than at the magnetic equator and mostly extends up to 20° on either side of the magnetic equator. Scintillation activity has also been reported to be dependent upon the solar activity [e.g. Kumar and Gwal, 2000; DasGupta, 2006].

Not much work has been done of GPS scintillations in the anomaly region of the South Pacific. The location of Suva (18.08° S, geomagnetic latitude: 21.07° S) provides with an excellent opportunity to study scintillations at the edge of the anomaly. The $S_4$ on L1 signal was computed by the GSV 4004B data acquisition system. The corrected value of $S_4$ to remove the effect of noise and multipath was estimated. Then this final $S_4$ was analyzed as described in section 2.2.4. In this chapter we present the diurnal, monthly and seasonal occurrences of weak, moderate and strong scintillation events at Suva, during 2010, a low solar activity year of current 24 solar cycle.

4.2 Results and Discussion

4.2.1 Diurnal and monthly occurrence of scintillations

In general, scintillations at low latitudes occur most frequently and are severe in the nighttime and equinoctial months [e.g. Basu and Basu, 1989; RamaRao et al., 2006a]. To examine the occurrence of amplitude scintillations of different strengths at Suva (geog. lat.18.15° S and geomag. lat. 21.07° S), a station near the equatorial
anomaly in the South Pacific region, the $S_d$ were recorded and the corrections to $S_d$ were applied as described in section 2.2.4. The daily scintillation events were inspected and classified into three categories; weak ($0.2 \leq S_d < 0.3$), moderate ($0.3 \leq S_d < 0.45$) and strong ($0.45 \leq S_d$) events [RamaRao et al., 2006b]. The occurrence of scintillations during each hour was noted as “yes” for 00:00-24:00 LT interval and by averaging over days of the months the diurnal monthly occurrence was calculated for different categories of scintillations. The diurnal monthly percentage occurrence of different categories of scintillations is shown in Figures 4.1a and 4.1b for January-June and July-December 2010, respectively. Local Time (LT) = UT + 12 hrs. It can be seen from these figures that weak scintillations occurred most predominantly in all the months of year 2010. The weak scintillation events occurred most frequently in January with maximum occurrence of 62.5% at 06:00 LT, followed (46%) in February at 01:00 LT, (43.7%), December between 06:00-12:00 LT, (32%), October at 06:00 LT, and (26.6%), November between 06:00-12:00 LT. The lowest occurrence of weak scintillations was observed in September and March during both day and night. The moderate scintillation events were most common in February with occurrence of 38.5% at 18:00 LT followed by 25% in December at 10:00 LT, 18.8% in January at 12:00 LT and 16.1% in October at 06:00 LT. No moderate events occurred in March, July and September months. The strong events were very rare and were observed only in January with occurrence of 12.5% at 06:00 LT, in May with occurrence of 3.2% at 07:00 LT and in August with occurrence of 2.4% at 12:00 LT.

Overall, it shows that scintillation occurred in the daytime and strong scintillation events were very rare. Thomas et al. [2001] studied nighttime L-band amplitude scintillations in Australia and South East Asia during 1998-1999 and found lower percentage occurrence at Darwin (12.4° S, Geomag. lat. 21.9° S) compared to other sites; Parepare (3.98° S), Pontianak (0.00° S), MarakParak (6.31° N) and Vanimo (2.4° S), located between the magnetic equator and the anomaly crest.
Figure 4.1 (a): Monthly diurnal variation of amplitude scintillation occurrences of weak, moderate and strong events at Suva during January 2010 to June 2010. The percentage occurrence of scintillations for each category shown was calculated hourly.
Figure 4.1 (b): Monthly diurnal variation of amplitude scintillation occurrences of weak, moderate and strong events at Suva during July 2010 to December 2010. The percentage occurrence of scintillations for each category shown was calculated hourly.
The measurement site, Suva is located at latitude of 18.08° S and geomagnetic latitude of 21.07° S, which is close to the location of Darwin, therefore, not much of strong scintillation events were expected during the low solar activity year 2010. The temporal variation of scintillation events was studied by dividing the period of occurrence into daytime (06:00-18:00 LT), pre-midnight (18:00-00:00 LT) and post-midnight (00:00-06:00 LT) period. Daytime scintillations have been observed in all the months of 2010. The monthly occurrence of weak, moderate and strong scintillation events in the daytime, pre-midnight and post-midnight period during January-June and July-December 2010 are shown in Figure 4.2a and 4.2b, respectively. A total of 480 scintillation patches were observed with 75 in January, 51 in February, 11 in March, 18 in April, 43 in May, 20 in June, 18 in July, 41 in August, 13 in September, 61 October, 68 in November and 61 in December. This indicates that scintillation activity was more pronounced in the October, November, December, and January months as compared to March and September where it was suppressed. The scintillation patches occurred most frequently in daytime during the months of January (57 events), October (51 events), February (47 events), December (47 events), and August (37 events), less in the pre-midnight period during the months of November (18 events), May (13 events), and June (10 events) and least in the post-midnight period with December (10 events), followed by January (9 events), April (9 events), May (9 events), October (7 events), and November (7 events). Interestingly, in March the pre-midnight scintillation was completely absent and in June the pre-midnight events were higher than both in the daytime and post-midnight periods. This clearly reveals that scintillation is not only a nighttime phenomenon, but predominantly a daytime phenomenon during the low solar activity. Daytime scintillations at L-band have also been observed at Lagos, Nigeria (6.5° N) by Adewale et al. [2012] and at Guilin (25.29° N), China, by Zou and Wang [2009]. Zou and Wang [2009] found that amplitude scintillations seldom occurred in the night (from 18:00 LT in the evening to 6:00 LT in the morning of the next day) during January 2007 to December 2008, a low solar activity years of 23 solar cycle. They observed only three nighttime amplitude scintillations events at Guilin.
Figure 4.2 (a): Monthly plots of number of weak, moderate and strong amplitude scintillation events in the daytime, pre-midnight and post-midnight periods at Suva from January 2010 to June 2010.
Figure 4.2 (b): Monthly plots of number of weak, moderate and strong amplitude scintillation events in the daytime, pre-midnight and post-midnight periods at Suva from July 2010 to December 2010.
Subsequently, Adewale et al. [2012] found that, in general, the $S_d$ was high during the post-midnight hours. They also reported that weak amplitude scintillations $(0.2 < S_d < 0.3)$ with peak percentage occurrences in the pre-midnight period of March (10%) and of April (9%). Moderate amplitude scintillation also were at peak in the pre-midnight of March (5%) and April (4%). Strong amplitude scintillations were most common during the post-midnight of March. However, strong daytime amplitude scintillations did occur during the months of March, April and August but their occurrence rates were below 1%.

Another feature of scintillations observed at Suva was that the strong scintillations $(0.45 < S_d)$, occurred only in January, May and August. In January one event occurred in the daytime, two events in the post-midnight period and in May and August one event each occurred in the daytime.

Our results are in very much agreement with the observations made by Kumar et al. [2007] at Suva from the IntelSat satellite transmitting on 3.925 GHz. They observed daytime scintillations with 83.4% occurrence, and only 9.6% of pre-midnight occurrence, while 6.8% of occurrence in the post-midnight period and suggested that daytime amplitude scintillations could be due to E-region irregularities. Earlier studies have shown that daytime scintillations are mainly associated with sporadic-E, except in polar and auroral regions [RamaRao et al., 1997]. Rastogi [1972] found a positive relationship between the sporadic-E and daytime scintillation and described some of the features of equatorial sporadic-E (Esq) as only a daytime phenomenon which disappears after sunset. Esq occurs at the base of the E-region (100 km) and can even disappear during magnetically quiet days. At times temporary disappearance during daytime was also found which Rastogi attributed to the imposition of additional westward electric field. Our results also compare well with some of other observations. Zou and Wang [2009] studied GPS ionospheric scintillations with $S_d \geq 0.2$, at Guilin (25.29° N), China, near the northern crest of EIA, during low solar activity years of January 2007 to December 2008. They found that the amplitude scintillations seldom occurred in the nighttime (18:00 – 06:00 LT) during both the years. Only three nighttime scintillation events were observed; 1 January 2007, 16 April 2007 and 5 February 2008, while strong amplitude scintillations with $S_d > 0.4$, occurred quite often in the daytime (06:00 –
18:00 LT). They also reported that the nighttime amplitude scintillations were associated with phase and TEC fluctuations. However, daytime strong amplitude scintillations with \( S_4 > 0.4 \) were usually associated with phase scintillations, whereas weak amplitude scintillations (0.2 \( \leq S_4 < 0.4 \)) and phase scintillations did not occur concurrently. Adewale et al. [2012] studied scintillations and TEC at Lagos (6.5° N), Nigeria, during February 2010 and August 2010 and found that the amplitude scintillation events not only occurred in the nighttime but also occurred in the day. Though, the \( S_4 \) increased during post-sunset hours, the daytime amplitude scintillations with \( S_4 > 0.4 \) were also observed. They also reported that nighttime amplitude scintillations were always associated with phase scintillations and TEC fluctuations, noting that VTEC depletions between 21:00 and 00:00 LT produced both amplitude and phase scintillations.

However, our findings disagree with most of the findings from the Indian and Brazilian anomaly sectors. GPS L-band scintillation activity was studied by RamaRao et al. [2006a; 2006b] under the GAGAN (GPS Aided GEO Augmented Navigation) project whereby a network was established to monitor GPS scintillations at 18 stations distributed all over India covering the geographic latitude from 8° to 32° N (Geomag. Lat., 1° S to 23° N). The results of GAGAN project during low solar activity period from January 2004 to July 2005 showed that maximum scintillations occurred in the post-sunset to midnight (19:00 – 00:00 LT) period with peak at around 21:00 LT. RamaRao et al. [2006c] compared VHF (FLEETSAT: 244 MHz) and L-band (INMARSAT: 1.5 GHz and GPS: L1-band 1575.45 MHz) scintillations recorded during 1998-1999 (HSSA) and 2004-2004 (LSSA) period at Waltair (17.7° N), a low latitude station. They found that scintillations at both the frequencies (1.5 GHz and 1.57542 GHz) show a high degree of similarity in the occurrence features mostly in the post-sunset hours, and the scintillations observed at GPS L1 frequency were always associated with TEC depletions or plasma bubbles. Muella et al. [2008] analyzed the scintillations at seven stations in the Brazilian region; Boa Vista (2.8° N), Manaus (3.1° S), Cachimbo (9.5° S), C. Grande (20.5° S), C. Paulista (22.4° S), S. J. Campos (23.1° S) and Palmas (26.4° S) during October and November 2002. They found highest level (\( S_4 \)) of scintillations mostly in the pre-midnight hours.
4.2.2 Seasonal occurrence of scintillations

As discussed in the earlier chapter, Fiji, experiences only two seasons; Hot and Wet season (November, December, January, February, March, April) and Cold and Dry season (May, June, July, August, September, October). The monthly data on weak, moderate and strong scintillation occurrences were divided into the two seasons and the seasonal percentage occurrences were calculated for the 24 hour period (00:00-24:00 LT) which are shown in Figures 4.3(a) and 4.3(b).

During the hot and wet season, the weak scintillation events were most frequent in the dawn period (04:00 – 07:00 LT), then decreased and again showed a peak at 10:00 LT. The minimum daytime occurrence was at 09:00 LT and 13:00 LT. The scintillation occurrences again enhanced in the pre-sunset at 18:00 LT but had less occurrence than the dawn period (04:00-07:00 LT). The moderate scintillations also showed a similar pattern, however, in this case the occurrence in the dusk period was higher than the dawn period. The strong scintillations ($S_4 > 0.45$) occurred only in the dawn period. Overall, the scintillation occurrence during the hot and wet season was highest in the dawn period followed by the pre-sunset hours. High occurrence of daytime scintillations has also been recorded between 10:00-12:00 LT.

The scintillations during the cold and dry season exhibited somewhat different occurrence characteristics. Overall occurrence of scintillations of all categories during cold and dry season was less as compared to hot and wet season. The weak scintillations showed a post-midnight maxima at 03:00 LT followed by a minima in the dawn period around 05:00 LT and a peak occurrence at 07:00 LT. Then the occurrence decreased but showed a minor peak at 10:00 LT. After that there was a point of no scintillation at 13:00 LT. An afternoon peak was recorded at 16:00 LT and in the dusk at 18:00 LT there were no scintillations recorded. A pre-midnight peak occurrence was also observed at 20:00 LT. The moderate scintillations showed a dawn peak at 06:00 LT and gradually decreased to no scintillation activity at 11:00 LT. The other major peak occurred in the afternoon at 16:00 LT and after that no scintillations were recorded. In this season the strong scintillations showed very little occurrence of about 1% at only 07:00 LT.
Hajkowicz and Dearden [1988] found an increase in the daytime VHF (150 MHz) amplitude scintillations recorded at Brisbane (27.4° S) during 1973-1985, a low sunspot activity period and found a pronounced increase in daytime scintillations

**Figure 4.3(a):** Variation of percentage occurrence of amplitude scintillations during hot and wet season, 2010 at Suva.

**Figure 4.3(b):** Variation of percentage occurrence of amplitude scintillations during cold and dry season, 2010 at Suva.
between 12:00-16:00 LT, during the southern winter throughout the solar cycle. They also found two peak occurrences in scintillation events during the southern summer; one in the daytime (08:00-10:00 LT) and the other in the pre-midnight period (20:00-22:00 LT) and scintillations were of quasi-periodic (QP) type. They also found an increase in QP type of scintillations with the decrease in sunspot numbers. Our results are consistent with these findings with peaks at 04:00-07:00 LT and another at 10:00 LT followed by a sunset peak at 18:00 LT during the hot and wet season. However, this is not the case during cold and dry season which showed a daytime peak at 07:00 LT.

The year 2010 was under low solar activity period with low SSN values throughout. The monthly average SSN values were: January – 9.2, February – 10.6, March – 12.3, April – 13.9, May – 15.4, June – 16.3, July – 17.7, August – 17.4, September – 19.6, October – 23.2, November – 26.5, December – 28.9 [IPS Radio and Space Services, 2013]. Thus, the solar activity does not have much effect on the scintillation occurrence. After the scintillation events were categorized into the daytime, pre-midnight and post-midnight, it was vividly clear that the daytime scintillation occurrence outweighed the nighttime occurrence as shown in Figures 4.4(a) and 4.4(b) for both the seasons. Comparing the occurrences in the two seasons, it is clear that, during hot and wet season, the daytime occurrence is high with a total of 166 weak events, 41 moderate events and only 1 strong event. During cold and dry, there were 108 weak, 20 moderate and 2 strong daytime events. The pre-midnight events during hot and wet season showed 36 weak events, 3 moderate and no strong events, while in the cold and dry season, there were 35 weak events with no moderate and strong scintillation events. The post-midnight of hot and wet season showed 30 weak events, 5 moderate and 2 strong scintillation events. During the cold and dry season the weak events are same, 30, while the moderate events reduced to 1 event and no strong events were observed. Since, the strong events are more deleterious to GPS L-band signals, our study of strong events shows no occurrence of strong scintillations in the pre-midnight of both the seasons. The strong events were observed in the daytime of cold and dry season and in the post-midnight of hot and wet season.

Basu et al. [1988] studied amplitude scintillations on 1.5 GHz signal from MARISAT satellite recorded at Huancayo (12° S) and Ascension Island (7.4° S) during
1979-1986 and found that seasonal occurrence pattern showing clear equinoctial peaks during low solar activity and vernal equinoctial peak during high solar activity with that, equatorial scintillations were more pronounced in the pre-midnight between 22:00-00:00 LT.

![Figure 4.4(a): Number of weak, moderate and strong amplitude scintillation events in the daytime, pre-midnight and post-midnight periods during hot and wet season, 2010, Suva.](image)

![Figure 4.4(b): Number of weak, moderate and strong amplitude scintillation events in the daytime, pre-midnight and post-midnight periods during cold and dry season, 2010, Suva.](image)

RamaRao et al. [2005] and RamaRao et al. [2006a] studied L-band nighttime scintillations under the GAGAN project at 18 stations during 2004-2005 and found that most of the L-band scintillations in the Indian region occurred in the pre-midnight period (19:00-24:00 IST) with very little occurrence in the post-midnight period. They
also found that in the Indian anomaly region the maximum L-band scintillation occurred in equinoctial months (March, April, September, October) which were confined to a latitudinal belt of 20° N during vernal equinox and 18° N in autumnal equinox. They observed almost no scintillations in the winter and summer months. RamaRao et al. [2006c] compared VHF (FLEETSAT: 244 MHz) and L-band (INMARSAT: 1.5 GHz as well as GPS: L1 1575.45 MHz) scintillations recorded during 1998-1999 (HSSA) and 2004-2004 (LSSA) period at Waltair (17.7° N), a low latitude Indian station. They found that at both the frequency bands, the scintillations were observed in the post-sunset hours during equinox and winter, whereas during summer the scintillations at GPS L-band were almost absent. Bhattyacharya et al. [2010] studied nocturnal variation of amplitude scintillations with data recorded at Bhopal (23.2° N), under the Indian EIA and found maximum scintillation occurrence in March and January months and minimum in November and May months. They found that in the equinoctial and winter months, scintillation occurrence was maximum in the pre-midnight period and minimum in the post-midnight period whereas during summer months scintillation occurrence was maximum in the post-midnight period and minimum in the pre-midnight period. Manju et al. [2011] studied L-band amplitude scintillations recorded at Trivandrum (dip: 0.5° N), India, during 2005-2005, a low solar activity period. They found that scintillations associated with ESF can begin as early as 16:00 IST, and then trace of ESF becomes weak between 19:45-20:45 IST with low $S_4$. Their seasonal results showed that scintillations were more common in the equinoctial months than in the solstice months during the solar minimum period. They also found maximum scintillation occurrence in vernal equinox, less in autumnal equinox and winter, and the least in summer. Paznukhov et al. [2012] recorded L-band scintillations during 2010 at ten locations in the African region and divided the stations into three regions namely; Atlantic, West and East. They found that during this low solar activity year of 2010, mostly weak scintillation events were observed and the scintillations were more predominant in the equinox in the Atlantic region (Ascension Island and Cape Verde). However, in West and East African regions weak scintillations were observed in boreal summer, while the equinoctial scintillations were statistically insignificant. Adewale et al. [2012] studied scintillations and TEC fluctuations at Lagos (latitude: 6.5° N),
Nigeria, during February 2010 and August 2010 and found that seasonally maximum scintillations occurred during equinox.

Generally, our finding shows maximum scintillation occurrence in January, February and December (summer months in the southern hemisphere) and minimum in March and September (equinoctial months). This up to some extent agrees with results of Paznukhov et al. [2012] during 2010 at ten stations over Africa, covering a latitude of 16.7° N to 8.0° S. However, disagrees with other findings from the Northern hemisphere specially the Indian and Nigerian low latitude stations [e.g. Basu et al., 1988; RamaRao et al., 2005; RamaRao et al., 2006a; RamaRao et al., 2006c; Bhattyacharya et al., 2010; Manju et al., 2011; Adewale et al., 2012]. Though daytime scintillation is more frequent, the results exhibits that seasonal pattern does exist in percentage occurrence of amplitude scintillation activity over Suva, but we need to extend the scintillation database for few more years before we can make a generalized statement on the seasonal variation of scintillation activity at Suva.

### 4.2.3 Annual occurrences of scintillations

On the whole, scintillation occurrence in 2010 is shown in Figure 4.5. Annually, the daytime weak scintillations had highest occurrences of 17.5% between 05:00-09:00 LT, with almost the same frequency of occurrence throughout the day, but the percentage occurrences decreased to 3.4% at around 13:00 LT. In the pre-midnight period weak scintillations were almost constant with occurrence rate of about 3%. In the post-midnight period the occurrence rate was around 2.5% till 02:00 LT, but decreased to 0% at 03:00 LT and again increased to 3.5%, showing the scintillation activity fluctuated. The moderate scintillation events were higher in the daytime with peak at 07:00 LT and then showed almost throughout the day with exception at around 13:00-14:00 LT, whereby no scintillation was recorded throughout the year. There was another pre-sunset peak in moderate scintillation occurrence at 17:00 LT. In the pre-midnight and post-midnight session, there was no occurrence of moderate scintillation events. During 2010 very few strong scintillation events were recorded and it only occurred during the dusk between 05:00-08:00 LT and the maximum percentage occurrence was 1.0%. Thus, generally, during the year 2010, a low solar activity period,
mostly weak scintillations were recorded at L-band. The scintillations were more pronounced during the daytime with the peak observed at dusk around 05:00-09:00 LT.

Figure 4.5: Annual percentage occurrence of amplitude scintillations during 2010 at Suva.

Figure 4.6 a, b, c); Percentage occurrence of weak, moderate and strong amplitude scintillation events in the daytime, pre-midnight and post-midnight periods and d) the percentage of annual total events in 2010 at Suva.
The annual occurrence of scintillation events is shown in Figure 4.5 which reveals that from a total of 405 weak scintillation events (Figure 4.6a), 68% occurred in the daytime, 17% the in pre-midnight and 15% in the post-midnight. From a total of 70 moderate events (Figure 4.6b), 87% of events occurred in the daytime whereas 4% in the pre-midnight and 9% in the post-midnight period. There occurred only 5 strong scintillation events (Figure 4.6c) of which 60% (3) occurred in the daytime whereas 40% (2) in the post-midnight with no event in the pre-midnight period.

Thus overall occurrence of scintillation events discloses that in the South Pacific region, Suva (18.15° S), the GPS signals are more deteriorated in the daytime in comparison to the pre-midnight and post-midnight periods during low solar activity period. Out of a total of 480 scintillation events which occurred during 2010 (Figure 4.6d), 71% of the events occurred in the daytime, 15% in the pre-midnight and 14% in the post-midnight period.

The results obtained on the occurrence of L-band scintillations at Suva could be explained by looking at studies carried out by other workers in the low latitude region. The L-band scintillations at the low latitude stations have been found to be highly correlated with the occurrence of equatorial spread-F (ESF) [Manju et al., 2011]. Mostly weak amplitude scintillations occur on L-band signals which as suggested by RamaRao et al. [2006b] is due to the presence of large scale size irregularities, low ambient electron densities and low electron density gradients at the equator during the low sun spot activity period. They also found that in Indian region, strong scintillations occur at and around the EIA region due to the presence of short scale length (~few hundred meters) irregularities and high ambient electron densities accompanied by large electron density gradient even during low sun spot activity periods.

The nighttime amplitude scintillations occur due to two types of irregularities namely, plasma bubbles induced (PBI) and bottom side sinusoidal (BSS) irregularities [RamaRao et al., 2005]. In the sunset and pre-midnight hours the F-region ambient ionization is relatively high with steep gradients in the electron density which are responsible for the generation of generalized Rayleigh-Taylor (GRT) instability, ranging from several kilometers to few centimeters. These irregularities cause range type spread-F on ionograms and strong scintillations on VHF signals and moderate
scintillations on L-band signals [RamaRao et al., 2005]. Basu and Basu [1989] reported that discrete amplitude scintillation patches were due to PBI while continuous scintillation events existing for longer durations were associated with BSS irregularities. The PBI developed due to GRT and rise due to non-linear evolution of $\mathbf{E} \times \mathbf{B}$ drift and produce scintillations at higher latitudes after some delay with respect to low latitude stations.

However, in our study, the daytime amplitude scintillations were more predominant than the nighttime. The daytime amplitude scintillations have been found to be associated with sporadic E-layer or the E-region irregularities [Dabas et al., 1992]. The sporadic E (Es) is a short-term phenomenon whereby high density ion layers form a narrow-altitude region in the E-layer. These irregularities are associated with the east-west electric field which drives the electrojet. The Es has been believed to be formed under the influence of atmospheric gravity waves and wind shear mechanism. Meteor showers, thunderstorms and lunar tides have also suggested to contribute to this type of irregularities [Rastogi, 1972]. In the equatorial region the Es is a daytime phenomenon with very little seasonal variation.

When considering the seasonal occurrence of amplitude scintillations, it has been found by many workers [e.g. RamaRao et al., 2006b; RamaRao et al., 2006c; Manju et al., 2011; Adewale et al., 2012; Paznukhov et al., 2012] that maximum amplitude scintillations occur in the equinox, less in winter and least in summer. An explanation of the equinox maxima was given by Tsunoda [1985]. He suggested that scintillation maximizes at times of the year when the solar terminator is most nearly aligned with geomagnetic flux tubes, i.e., when the height-integrated E-region Pedersen conductivity changes most rapidly. This simultaneously decreases the conductivity of the E-region which is magnetically conjugate to the F-layer during sunset hours and thus acts as a short circuit over the sunlit hemisphere. In this work, it has been observed that scintillation occurrence is more in the hot and wet season when compared to the cold and dry season. The frequency as well as the intensity of the amplitude scintillations increased in the hot and wet season. This contradicts the results reported by workers in low latitude regions of the northern hemisphere during the previous low solar activity phases. The hot and wet season corresponds to summer in the northern
hemisphere and cold and dry corresponds to winter. Several researchers from scintillation studies in northern hemisphere have reported high scintillation occurrence in winter than the summer season and in some cases even scintillation was absent in summer [e.g. RamaRao et al., 2006b; RamaRao et al., 2006c; Manju et al., 2011; Adewale et al., 2012]. Paznukhov et al. [2012] did observe increased scintillation events during summer compared to equinoctial months in the Western and Eastern African region as discussed before. Though this is not fully explained, they suggested that maybe in African region the weak EPB’s do not always evolve into the fully developed plumes with the associated small scale turbulent structures that cause GPS scintillations. Another suggestion was that although plasma bubbles were present, the total integrated density fluctuation (which can be limited by the background plasma density) along the GPS ray path is insufficient to produce signal scintillations at the L-band frequency. From the amplitude scintillation data recorded on VHF (150 MHz) at Brisbane (27.4° S) during 1973-1985, a low sunspot activity period Hajkowicz and Dearden [1988] found an obvious increase in daytime scintillations between 1200-1600 LT, in the southern winter throughout the solar cycle with two peak occurrences in scintillation events during the southern summer; one in the daytime (08:00-10:00 LT) and the other in pre-midnight period (20:00-22:00 LT). RamaRao et al. [1997] studied scintillations with data recorded at 244 MHz signals from FLEETSAT satellite at Waltair (17.7° N), India, during 1983-1993, over a solar cycle. They found that the occurrence of daytime scintillations was a typical feature of low latitude region during low solar activity period in the summer months. They found occurrence of daytime scintillations to be maximum during summer (15%) of low solar activity (1985-1986) and minimum during the equinoctial months (2%) of high solar activity (1989-1990). They also computed the correlation coefficient of the scintillation activity with $F_{10.7}$ and found a negative coefficient. The correlation coefficient of $F_{10.7}$ was negative and maximum in summer (-0.64) and minimum in equinox (-0.31). Singh et al. [2009] studied scintillations using the data recorded on 250 MHz beacon signals from FLEETSAT satellite at Varanasi (14.92° N), India, during January 1991 to December 1993 (declining phase of low solar cycle) and during April 1998 to December 1999 (ascending phase of the consecutive solar cycle). They found that maximum occurrence
of daytime scintillations is observed at around 15:45 LT during all seasons with daytime scintillations having slow fade rates. They related the occurrence of daytime scintillations with sporadic-E layer and found that more than 60% of the daytime scintillation occurrences were associated with $f_{o}E_s \geq 5$ MHz while the association with $f_{o}E_s \geq 4$ MHz was found to be 75%. It is known that mid-day summer scintillation has a high probability of occurrence when $f_{o}E_s \geq 5$ MHz. In another study at Varanasi (14.92° N), India, during 1991 to 1999, using the data recorded from FLEETSAT satellite (250 MHz), Patel et al. [2007] from the occurrence rate of daytime scintillations, in general, showed that the sporadic-E irregularity occurs maximum in winter months and less in equinox months and least in summer months. Patel et al. [2009] in the study of quasi-periodic scintillations using the data recorded from FLEETSAT satellite (250 MHz) at Varanasi (14.92° N), India, during 1991 to 1999, found that daytime scintillations showed maximum between 16:00-18:00 LT and a minimum between 06:00-08:00 LT whereby the peak occurrences were associated with sporadic-E irregularities.

4.2.4 Strong amplitude scintillation events and their association with TEC, phase scintillations and C/No variations

Further analysis has been carried out to find the association of strong amplitude scintillation events on the GPS signals with the phase scintillations, VTEC and carrier to noise (C/No) variations. We categorized strong amplitude scintillation events according to the criteria proposed by RamaRao et al. [2006b] and Bhattcharyya et al. [2010] for low latitude scintillations. A total of five strong scintillation events were observed during 2010 which are shown in Figure 4.7(a-e). The 18 January (Fig. 4.7a), 26 May (Fig. 4.7d) and 10 August (Fig. 4.7e) events occurred in the daytime, while, 20 January (Fig. 4.7b) and 30 January (Fig. 4.7c) events occurred in the post-midnight period.

It can be seen from Figure 4.7(b, c) that phase scintillation does occur in association with post-midnight strong amplitude scintillation events. While, in the daytime (Figure 4.7a, d, e), one (Figure 4.7a) out of the three events showed phase scintillations associated with amplitude scintillations.
Figure 4.7(a-b): Time variation of amplitude and phase scintillation, TEC, TEC Rate and Carrier to Noise ratio of the strong scintillation events experienced by satellite PRN-14 at Suva on: a) 18 Jan, b) 20 Jan,  2010.
Figure 4.7(c): Time variation of amplitude and phase scintillation, TEC, TEC Rate and Carrier to Noise ratio of the strong scintillation event experienced by satellite PRN-22 at Suva on 30 Jan, 2010.
Figure 4.7(d): Time variation of amplitude and phase scintillation, TEC, TEC Rate and Carrier to Noise ratio of the strong scintillation event experienced by satellite PRN-7 at Suva on 26 May, 2010.
Figure 4.7 (e): Time variation of amplitude and phase scintillation, TEC, TEC Rate and Carrier to Noise ratio of strong the scintillation event experienced by various satellite PRN-5 at Suva on 5 Aug, 2010.
The daytime strong events did not show considerable TEC fluctuations, however, in the post-midnight, one (Figure 4.7b) out of the two events showed TEC depletion by almost 0.5 TECU, which may be associated with plasma bubble. There was a decrease in carrier to noise ratio in all the cases of strong scintillation events. The carrier to noise ratio decreased with increase in the $S_4$ level. The observations made by Zou and Wang [2009] at Guilin (25.29° N) showed phase and TEC fluctuations were associated with nighttime amplitude scintillations. They suggested that daytime scintillations are caused by small scale irregularities in the ionospheric E-region. They also observed that strong daytime amplitude scintillations were associated with phase scintillations, whereas weak daytime scintillations were not associated with phase scintillations. Moreover, TEC depletions and Rate of TEC were much weaker when compared with nighttime scintillations. The strong amplitude scintillations observed showed phase fluctuations especially in the morning, but pure daytime events did not show any phase fluctuation at all. At Lagos, Nigeria, Adewale et al. [2012] found that enhanced nighttime amplitude scintillations always occurred with enhanced nighttime phase fluctuations which is consistent with our results of strong post-midnight scintillations. RamaRao et al. [2006b] suggested that the nighttime L-band scintillations near the crest of the anomaly region, in India, were associated with the plasma bubbles which were detected as TEC depletions. The TEC depletions smaller than 2 TECU do not produce GPS scintillations and the strength of scintillation is determined by the background density that the bubble intersects, most probably a larger background density can admit larger density fluctuations [Paznukhov et al., 2012]. Beach and Kitner [1999] carried out investigations at Ancon (dip latitude. 0.8° N) and did observe cases whereby TEC fluctuations were constant, but the $S_4$ level increased. In our investigation, we did observe a case of TEC depletion associated with strong amplitude scintillation as in Figure 4.6b which occurred in the post-midnight period. This post-midnight strong scintillation event may have occurred due to PBI irregularities and the daytime strong events could most likely be associated with sporadic-E or the E-region irregularities, since in all the cases of strong daytime scintillations events, there were no evidence of TEC depletions. The sporadic-E layer forms near the base of the E-region (100 km), due to the plasma gradient or cross-field instability [Rastogi, 1972]. The
equatorial sporadic-E (Esq) is characterized as thin and patchy layers of enhanced electron density which could last from minutes to hours [Wu et al., 2005]. Since, Esq is formed due to enhanced electron content, the non evidence of depletions affirms that daytime scintillations could not be due to plasma depletions/bubbles. The enhancement may not be too high and could be masked by the high electron density of the F1- and F2-layers in the daytime and due to this not much TEC fluctuations may have been recorded with strong daytime amplitude scintillations.

On the other hand, signal to noise ratio does show a drop and a drop below the receiver threshold level could result in loss of lock [RamaRao et al., 2006a]. Rapid phase variations cause a doppler shift in the GPS signals, which may exceed the bandwidth of the phase lock loop (PLL), resulting in loss of lock of phase [RamaRao et al., 2006b].

4.3 Conclusions

A preliminary study on the ionospheric L-band scintillation was carried out using the GPS signal recorded for one year (2010) at Suva, a low solar activity year of current 24th solar cycle. The main results of the study are summarized as follows:

- Diurnal variation revealed that L-band amplitude scintillation was more pronounced in the daytime with peak occurrence between at 07:00 LT as compared to the nighttime period. January showed the highest number of daytime scintillation events, while March and September showed the least.

- The occurrence of weak, moderate and strong scintillation events showed that, weak scintillation events were most common (84% of 480 events) and occurred in all the months of 2010. Weak events showed highest occurrence in January followed by February and December. The least occurrence of weak events was recorded in September and March. The moderate scintillation events were most common in February and no moderate events were recorded in March, July and September. The strong events were very rare and observed in only January, May, and August. Out of 5 events observed, 3 occurred in the daytime and 2 in the post-midnight period.
• Seasonal variation showed a higher percentage of scintillation occurrences in hot and wet season compared to cold and dry season. There were 59% of scintillation events in hot and wet season of which 43.3% in daytime, 8.1% in the pre-midnight and 7.6% in post-midnight period. While in the cold and dry season 41% of scintillation events were recorded of which 27.1% were daytime events, 7.3% pre-midnight events and 6.6% post-midnight events. This shows that hot and wet season seems to be more problematic to satellites RF signals since the occurrence of amplitude scintillations is enhanced during this time.

• Annual results showed there were 71% of daytime events with peak occurrences between 05:00-09:00 LT. Followed by that was pre-midnight occurrence of 15% and then the post-midnight of 14%. Weak scintillation events were recorded the most (84.4%), followed by moderate events (14.6%) and the strong events were recorded the least (1%) in this low phase of solar activity.

• The analysis of strong scintillation events showed that phase scintillations are associated with post-midnight amplitude scintillation events but not in the daytime. No significant TEC fluctuations were associated with strong daytime amplitude scintillation events, however, post-midnight strong scintillation did show TEC fluctuation. A decrease in carrier to noise ratio was recorded in all the strong scintillation events and the carrier to noise ratio decreased with an increase in $S_4$. 
Chapter 5 Effects of Geomagnetic Disturbances on the Ionospheric TEC and Scintillations

This chapter deals with the geomagnetic disturbances effects on the GPS based TEC and L1-band scintillations recorded at Suva during 2010. The TEC and scintillations on the GPS L1-band signals are being recorded at every minute from all the visible satellites since January 2010. The $Dst$ values and geomagnetically quiet (Q) and disturbed (D) days were attained from the World Data Center for Geomagnetism (http://wdc.kugi.kyoto-u.ac.jp/dst_realtime/presentmonth/index.html), Kyoto, Japan and the sudden storm commencement (SSC) times from the National Geophysical Data Center (ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUDDEN_COMMENCEMENTS/STORM2.SSC). The storms were classified into SSC or SGC types on the basis of SSC times and further classified into weak, moderate and intense according to their respective minimum $Dst$ values. The storms were again grouped according to the occurrence of their main phase in; daytime, pre-midnight, and post-midnight periods as category A, B and C, respectively.

5.1 Introduction

Space weather phenomenon, particularly solar activity is the main controlling factor of geomagnetic disturbances which affect the F-region of the ionosphere [Lastovicka, 2005]. This has been known for a long time that the Sun is the integral part of space weather and has the major effect on the ionospheric F-region of the Earth. One of the important domains of space weather is the geomagnetic storms. Geomagnetic storms are found to be initiated by solar disturbances. Geomagnetic storm refers to the geomagnetic effects of a magnetospheric storm which is any large prolonged disturbance of the magnetosphere by variations in the solar wind [Knecht and Shuman, 1985]. The principal feature of a magnetic storm is an unmistakable decrease in the horizontal component of the Earth’s magnetic field intensity and its subsequent recovery [Gonzales et al., 1994]. During a geomagnetic storm, Sun’s magnetic field
called the interplanetary magnetic field (IMF) is southward for a substantial length of
time which allows a lot of solar wind energy into the magnetosphere-ionosphere system
[Kumar et al., 2005]. The strength of magnetic storms at low latitudes is measured
through the ring current index Dst which is the magnitude of the normalized horizontal
component of the Earth’s magnetic field (axially symmetrical disturbance) determined
from the data obtained by low latitude observatories distributed in longitude on an
hourly basis [Knecht and Shuman, 1985].

The low latitude ionospheric F-region has a characteristic feature known as the
equatorial anomaly, whereby, in the daytime, the fountain effect due to \( \mathbf{E} \times \mathbf{B} \) drift lifts
the equatorial plasma upwards, which then diffuses downwards along the magnetic field
lines on either side of the equator. During geomagnetic storms, the structure of this
anomaly can change. Basu and Bhattacharya [2002] found that at low latitudes it is
difficult to distinguish magnetic-storm effects because of the large ionospheric
variability even during quiet times. However, some workers [e.g. Li et al., 2008; Fejer
et al., 1999; Sastri et al., 1997] have found that during geomagnetic storms, the
equatorial electric fields could be affected by two high latitude sources which are; solar
wind-magnetosphere dynamo (direct or prompt penetration of the magnetospheric
convection electric field) and the ionospheric disturbance dynamo. The theory of the
magnetic storms is well developed, however, the prediction of effects of individual
storms is not yet possible since each storm is unique and can have different effects on
the ionosphere [Bhattacharya et al., 2002].

It is recognized that one of the most important effects of space weather is on the
trans-ionospheric radio wave propagation, which is severely affected by the ionospheric
scintillations mainly during intense storm time [Kumar et al., 2005]. Radio waves
recorded at the ground stations transmitted from satellites give information about the
ionospheric irregularities. Generally, if the main phase of the storm as measured by Dst
occurs during the day 10:00-16:00 LT, then the layer height would not rise and F-region
irregularities would not develop. If the minimum of Dst (i.e. maximum of storm)
occurs in the post-sunset to midnight period (pre-midnight) the effect of magnetic
activity is little since the F-layer height has already risen and if the maximum activity
occurs in the post-midnight period (till 05:00 LT), a plume can develop due to the rise
of the F-layer caused by the eastward electric field and thus TEC fluctuations and scintillations may be observed on trans-ionospheric paths [Aarons et al., 1997]. These, indeed, justify some of the storms, however, each magnetic storm has a distinct pattern and the state of the ambient as well as the state of the equatorial ionosphere at the commencement of the storm are also thought to be imperative. In view of this several studies [e.g. Aarons et al., 1997; Yizengaw and Essex, 1999; Kumar and Gwal, 2000; Bhattacharya et al., 2002; Basu and Bhattyacharya, 2002; Kumar et al., 2005; Araujo-Pradere et al., 2006; Basu et al., 2007; Dashora and Pandey, 2007; Li et al., 2008; Jain et al., 2010; Priyadarshni and Singh, 2011] have examined the effects of geomagnetic activity on scintillations at low and equatorial latitudes.

Storms are usually classified into three categories according to the occurrence time of their main phase in the local time; category A: daytime (06:00-18:00 LT), category B: pre-midnight (18:00-00:00 LT) and category C: post-midnight (00:00-06:00 LT) [Kumar et al., 2005]. The effects of category A storms were studied by Bhattacharya et al. [2002] and Aarons et al. [1997] and they found that in most cases scintillations began after sunset and lasted till post-midnight period. From a study on category B storm effect on scintillations, Bhattacharya et al. [2002] reported scintillation occurrences after sunset on storm day and lasted just after 23:00 LT. The category C storm effects were studied by Aarons et al. [1997] and Bhattyacharya et al. [2010] who observed scintillations near sunset and in the post-midnight period and none in the daytime. However, Priyadarshni and Singh [2011] from their study of category C storm effects reported suppression of GPS scintillations during the main phase of the storms.

In other studies Bhattyacharya et al. [2002] studied scintillations during magnetically disturbed days in 1999 and found that longer-lived perturbation drifts were produced by a disturbance dynamo during magnetically disturbed periods after 22:00 LT. DasGupta [2006] studied storm-time scintillations at an Indian low latitude station, Calcutta (22.58° N) during the equinoctial months of 2000 and found that the scintillations activity is reduced during magnetically active periods. In the local summer (Indian Time) months, the occurrence of scintillations is more in magnetically active periods than in the quiet periods [DasGupta, 2006]. Although, several studies on
scintillation activity during geomagnetic disturbances have been carried out, but none so far from the South Pacific region.

The TEC has also been found to be affected by geomagnetic storms. The interaction between solar wind and magnetosphere under southward interplanetary magnetic field causes an instantaneous penetration of electric field or prompt penetrating electric field (PPE) from high latitude to the mid and low latitudes mainly during intense storms [Basu et al., 2007]. A PPE can cause large dayside enhancement in TEC at low latitudes due to uplifting of the ionospheric F-region while, at the nightside a decrease is experienced due to downward drift and collapse through recombination. On the other hand, disturbance dynamo electric fields (DDE) begins to dominate the low latitude electrodynamic processes within a few hours from the onset of the storm which is always in opposite direction to the normal ionospheric electric field [Blanc and Richmond, 1980; Kumar et al., 2005; Jain et al., 2010]. The response of ionospheric F2-region to a geomagnetic storm is called an ionospheric storm. The storm could either be positive if an increase in \( f_0F_2 \) occurs or negative if a decrease in \( f_0F_2 \) occurs or of no change if there is no significant change in \( f_0F_2 \) during the main phase of the storm and this largely depends on the storm-time, intensity, station latitude and the location of the station in the winter or summer hemisphere [Kumar, 2005]. Since the F-region has the highest concentration of electrons, the overall TEC could either be enhanced (positive storm) or reduced (negative storm) accordingly.

The category A storm effects on TEC have been studied by many researchers [e.g. Pandey and Dashora, 2006; Dashora and Pandey, 2007; Jain et al., 2010; Bagiya et al., 2009] who mostly found enhancement in TEC during main and recovery phases. Yizengaw and Essex [1999] studied a category B storm effect and found TEC depletions in the mid-latitude, while at the high-latitude and the low latitude station, the increase in TEC was more pronounced during the main phase of the storm. A category C storm effect was studied by Wu et al. [1997] at Taiwan using 9 observational sites covering latitudes between 21.9° - 26.2° N and they found that during the main phase, the average diurnal peak VTEC at all stations increased from the average quiet time of 21.14 to 26.3 TECU.
In this chapter effect of geomagnetic disturbances and storms (severe disturbances) on scintillation and TEC has been studied at Suva during 2010. The TEC and scintillation data were separated on five internationally Q- and D-days from each month which were then combined to examine seasonal and annual geomagnetic disturbance effect. The storm effect of different strength and intensity were then examined for the period of 2010-2011 using the SSC and $Dst$ index data from WDC for Geomagnetism, Kyoto, Japan, and NGDC, respectively.

5.2 Results and Discussion

5.2.1 Geomagnetic disturbance effect on scintillations

International five quiet (Q) and five disturbed (D) days in a month were attained from the average magnetic disturbances classified by geomagnetic indices $Kp$ and $Ap$. The Q- and D-days were noted from the WDC (http://wdc.kugi.kyoto-u.ac.jp/cgi-bin/qddays-cgi). The percentage occurrence of GPS scintillations has been separated on the five Q- and five D-days of every month in 2010 for weak, moderate and strong scintillation events. Then monthly occurrences were grouped into the two seasons; Hot and Wet (November, December, January, February, March, April) and Cold and Dry (May, June, July, August, September, October) seasons and plotted as in Figure 5.1a-d. Generally, during hot and wet season, the scintillation activity seems to be increased on the disturbed days, while during the cold and dry season, the scintillation activity does not vary significantly. Comparison of the weak scintillation occurrence on Q- and D-days in the cold and dry season shows that in the daytime of both Q- and D-days there are two common peak occurrences; one around 07:00-08:00 LT, and the other around 16:00-17:00 LT, while on D-days an additional peak is shown at 15:00 LT. Apart from this extra peak, the percentage occurrences are almost the same. The pre-midnight of Q-days show variations in the percentage occurrences, while D-days show that scintillation commence around 21:00 LT and last until past-midnight.
Figure 5.1: Seasonal percentage occurrence of scintillations on Q- and D-days, a) Cold and dry Q-days, b) Cold and dry D-days, c) Hot and wet Q-days, d) Hot and wet D-days.
In the post-midnight period, on Q-days the weak scintillation activity is only found at around 04:00 LT, while in the D-days, the weak scintillations are found to occur almost throughout the period with exception to around 03:00 LT. There were no moderate scintillation events recorded in the pre-midnight and post-midnight periods on both Q- and D-days, however, during daytime two peaks were recorded. On Q-days one peak occurred at 09:00 LT, and the other at 17:00 LT, while on D-days one peak occurred at around 07:00-08:00 LT and the other at around 17:00 LT. No strong events were recorded on Q- and D-days of cold and dry season.

During the hot and wet season, when the occurrence of weak scintillation events is compared on Q- and D-days it is evident that in the daytime, the occurrence rate of weak scintillations increases on the D-days with peak at 11:00 LT with an afternoon peak at around 14:00-16:00 LT, while on Q-days only one peak occurrence is recorded at 07:00 LT. In the pre-midnight period peak occurrence of scintillation is found on both Q- and D-days at 19:00 LT, however, the peak is enhanced on the D-days. In the post-midnight period, on Q-days, the weak scintillations occurred before 03:00 LT and is almost same for the D-days. The moderate scintillation events were also increased on D-days. In the daytime of Q-days, moderate scintillation events are only recorded at 06:00 LT and in the afternoon period at around 16:00-18:00 LT, however, on D-days, moderate scintillation peak occurrences showed peaks at 07:00 LT, 10:00 LT and 18:00 LT. There were moderate scintillations almost throughout the day with no events between 08:00-09:00 LT and 13:00-14:00 LT intervals. In the pre-midnight of Q-days, no scintillation events occurred, while on the D-days scintillation events were recorded at around 19:00 LT which died out after 20:00 LT. In the post-midnight period, no moderate scintillation events were recorded on both the Q- and D-days. The strong scintillation events were not recorded on Q-days, while, strong events were recorded around 06:00 LT on D-days.

Hence, on the D-days the scintillation is generally found to increase. During the cold and dry season, the peak occurrences are almost same, however, on D-days scintillations are found almost throughout the day. During hot and wet, the percentage occurrence of scintillation shows a vast increase as compared to the occurrence on Q-days.
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Figure 5.2: Annual percentage occurrence of scintillations on Q- and D-days, a) Q-days, b) D-days.
When the annual occurrence of scintillations on Q- and D-days is compared, generally it is seen that scintillation occurrence in the daytime and in the pre-midnight on Q-days is increased as shown in Figure 5.2a-b. The weak scintillation occurrence in the daytime is increased on D-days. There is a distinct early morning peak between 06:00-09:00 LT on both Q- and D-days. The peak on D-days is larger than Q-days by ~5%. The secondary peaks in scintillation are found at around 10:00 LT and around 15:00 LT on D-days. On D-days the pre-midnight scintillation occurrence is again increased, though the peaks occur at 19:00 LT and 21:00 LT on both Q- and D-days. However, in the post-midnight period, weak scintillation events do not show any appreciable variation. Considering the moderate scintillation events, the daytime increase is obvious, with peak occurrences at 07:00 LT, 10:00 LT, and 18:00 LT on D-days. In the pre-midnight and post-midnight periods on both Q- and D-days, no moderate scintillation event was recorded. The strong scintillation events occurred at 06:00 LT on D-days with a total occurrence of about 4%. Thus annual variation of scintillation occurrence also shows an increase in the frequency and intensity of amplitude scintillations on D-days when compared to the Q-days.

Bhattyacharya et al. [2002] studied scintillations on 244 MHz signals from FLEETSAT satellite at Ancon (11.8° S) during two magnetically active periods in 1999; first during 18-19 February 1999 and during 1 March 1999 and found that the irregularities may be freshly generated in the post-midnight period. DasGupta [2006] studied amplitude scintillations on L-Band signals from INMARSAT (1.5 GHz) and GPS (1575.42 MHz) as well as VHF signal from FLEETSATCOM (244 MHz) at Calcutta (22.58° N), India, recorded during 1996 to 2000 (nearly half solar cycle) under Q- and D-days and storm conditions. He observed that during the equinoctial months (August-October and February-April), the occurrence of scintillations was more during magnetically active periods (D-Days) than during quiet periods except in April 2000. In summer months of May-July (like May 1998, May 1999, July 2000), the occurrence of scintillations again increased during magnetically active periods compared to quiet periods.

Observations of ionospheric scintillations have been used to gather information and to study the ionospheric irregularities [Bhattacharya, 1991]. The results attained
reveal that, in general, an increase in the occurrence of scintillation on disturbed days which is attributed to the formation of new irregularities in the ionosphere. In our study more of weak amplitude scintillations have been recorded on D-days as compared to Q-days. It has been found that weak amplitude scintillations are associated with irregularities with scale size equal to Fresnel dimensions [Bhattacharya, 1991]. The Fresnel dimension is given by \( \frac{2\lambda Z_R}{\lambda} \) where \( \lambda \) is the signal wavelength, \( Z_R \) is the effective distance of the irregularity layer from the receiver. On magnetically disturbed days, the perturbation electric field associated with the Rayleigh-Taylor plasma instability, produces the equatorial spread-F (ESF) irregularities that give rise to the scintillations [Engavale et al., 2006]. When this perturbation electric field dies out, the irregularities drift into the background plasma. To further examine the effects of severe magnetic activity on scintillations i.e. irregularities, scintillations during magnetic storms have been presented in the next sub-section.

5.2.2 Effects of geomagnetic storms on scintillations

The strength of geomagnetic storms at low latitudes is measured using the \( Dst \) index. A total of 17 geomagnetic storms were identified during the two year period of January 2010 to December 2011. The first set of storms were selected by storm sudden commencement (SSC) time from the NGDC (ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUDDEN_COMMENCEMENTS/STORM_M2.SSC), USA, and grouped into SSC storms. The second set of storms for which SSC data has not been updated yet on NGDC was selected by \( Dst \) index being less than -50 nT and the day being classified as magnetically disturbed in the WDC for Geomagnetism (http://wdc.kugi.kyoto-u.ac.jp/cgi-bin/qddays-cgi), Kyoto, Japan. These storms were classified as storm gradual commencement (SGC) types. The scintillation occurrence was identified from the onset of the storm (Day 0) to a day or two after the storm onset, Day 1 and Day 2, respectively, to understand how the scintillation activity changes with category and intensity of storms. The variation of scintillation activity in the day, pre-midnight and post-midnight periods was examined for day 0–2. Table 5.1a
Chapter 5  Effects of Geomagnetic Disturbances on the Ionospheric TEC and Scintillations

and 5.1b give the general features of the storms for which the scintillation data were available.

Table 5.1a: SSC type geomagnetic storms during 2010 and 2011

<table>
<thead>
<tr>
<th>S. No</th>
<th>SSC Day/Time</th>
<th>Main Phase (Day: Time)</th>
<th>Min. Dst (nT) Day: Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5 Apr 10 20:26</td>
<td>5th-7th Apr 01:00-03:00</td>
<td>-73 7th ~ 03:00</td>
</tr>
<tr>
<td>2</td>
<td>12 Apr 10 01:04</td>
<td>12th-14th Apr 05:00-14:00</td>
<td>-56 12th ~ 14:00</td>
</tr>
<tr>
<td>3</td>
<td>2 May 10 21:08</td>
<td>5th 00:00-04:00</td>
<td>-67 5th ~ 07:00</td>
</tr>
<tr>
<td>4</td>
<td>28 May 10 14:58</td>
<td>29th 09:00-00:00</td>
<td>-85 30th ~ 01:00</td>
</tr>
<tr>
<td>5 &amp; 6</td>
<td>4 Aug 10 05:00</td>
<td>4th 08:00-12:00</td>
<td>-65 4th ~ 17:00</td>
</tr>
<tr>
<td></td>
<td>4 Aug 10 22:19</td>
<td>5th 23:00-01:00</td>
<td>-64 5th ~ 08:00</td>
</tr>
</tbody>
</table>

Table 5.1b: SGC type geomagnetic storms during 2010 and 2011

<table>
<thead>
<tr>
<th>S. No</th>
<th>SGC Day</th>
<th>Main Phase (Day: Time)</th>
<th>Min. Dst (nT) Day: Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>11 Oct 10</td>
<td>11th 22:00-02:00</td>
<td>-78 12th ~ 07:00</td>
</tr>
<tr>
<td>8</td>
<td>4 Feb 11</td>
<td>5th 06:00-10:00</td>
<td>-56 5th ~ 10:00</td>
</tr>
<tr>
<td>9</td>
<td>1 Mar 11</td>
<td>1st 22:00-03:00</td>
<td>-61 2nd ~ 03:00</td>
</tr>
<tr>
<td>10</td>
<td>10 Mar 11</td>
<td>10th 13:00-10:00</td>
<td>-80 11th ~ 18:00</td>
</tr>
<tr>
<td>11</td>
<td>6 Apr 11</td>
<td>6th 22:00-07:00</td>
<td>-61 7th ~ 08:00</td>
</tr>
<tr>
<td>12</td>
<td>5 Aug 11</td>
<td>8th 08:00-12:00</td>
<td>-113 8th ~ 16:00</td>
</tr>
<tr>
<td>13</td>
<td>9 Sept 11</td>
<td>10th 02:00-06:00</td>
<td>-60 10th ~ 06:00</td>
</tr>
<tr>
<td>14</td>
<td>17 Sept 11</td>
<td>17th 21:00-00:00</td>
<td>-63 16th ~ 04:00</td>
</tr>
<tr>
<td>15</td>
<td>26 Sept 11</td>
<td>27th 04:00-07:00</td>
<td>-103 27th ~ 12:00</td>
</tr>
<tr>
<td>16</td>
<td>24 Oct 11</td>
<td>25th 10:00-14:00</td>
<td>-137 25th ~ 14:00</td>
</tr>
<tr>
<td>17</td>
<td>1 Nov 11</td>
<td>1st 07:00-19:00</td>
<td>-61 2nd ~ 04:00</td>
</tr>
</tbody>
</table>

The storms shown in Table 5.1a and 5.1b were categorized into category A, B and C according to their occurrence time of the main phase as described in section 2.2.3. Tables 5.2a, 5.2b, 5.2c show the occurrences of scintillations under category A, B and C storms, respectively. The storms have also been classified according to the Dst values into moderate (-100 nT ≤ Dst < -50 nT), intense (-200 nT ≤ Dst < -100 nT) and very intense (Dst < -200 nT), in order to examine the effect of storm intensity on scintillations as well. There were no very intense storms during 2010-2011.
### Table 5.2a: Effect of category A geomagnetic storms on scintillation activity (-: no scintillation, *: weak scintillation, \(\Delta\): moderate scintillation, \(\gamma\): strong scintillation and ND: no data). The main phase of category A storms occurs in the daytime period.

<table>
<thead>
<tr>
<th>Storm No.</th>
<th>Intensity</th>
<th>Day 0</th>
<th>Day 1</th>
<th>Day 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Post</td>
<td>Day</td>
<td>Pre</td>
</tr>
<tr>
<td>2</td>
<td>Moderate</td>
<td>*</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>Moderate</td>
<td>*</td>
<td>(\Delta)</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>Moderate</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>Moderate</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>Intense</td>
<td>-</td>
<td>*</td>
<td>-</td>
</tr>
<tr>
<td>15</td>
<td>Intense</td>
<td>-</td>
<td>*</td>
<td>-</td>
</tr>
<tr>
<td>16</td>
<td>Intense</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

### Table 5.2b: Effect of category B geomagnetic storms on scintillation activity (-: no scintillation, *: weak scintillation, \(\Delta\): moderate scintillation, \(\gamma\): strong scintillation and ND: no data). The main phase of category B storms occurs in the pre-midnight period.

<table>
<thead>
<tr>
<th>Storm No.</th>
<th>Intensity</th>
<th>Day 0</th>
<th>Day 1</th>
<th>Day 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Post</td>
<td>Day</td>
<td>Pre</td>
</tr>
<tr>
<td>4</td>
<td>Moderate</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>14</td>
<td>Moderate</td>
<td>-</td>
<td>*</td>
<td>-</td>
</tr>
<tr>
<td>17</td>
<td>Moderate</td>
<td>-</td>
<td>*</td>
<td>(\Delta)</td>
</tr>
</tbody>
</table>

### Table 5.2c: Effect of category C geomagnetic storms on scintillation activity (-: no scintillation, *: weak scintillation, \(\Delta\): moderate scintillation, \(\gamma\): strong scintillation and ND: no data). The main phase of category C storms occurs in the post-midnight period.

<table>
<thead>
<tr>
<th>Storm No.</th>
<th>Intensity</th>
<th>Day 0</th>
<th>Day 1</th>
<th>Day 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Post</td>
<td>Day</td>
<td>Pre</td>
</tr>
<tr>
<td>1</td>
<td>Moderate</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>Moderate</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>5 &amp; 6</td>
<td>Moderate</td>
<td>*</td>
<td>*</td>
<td>(\Delta)</td>
</tr>
<tr>
<td>7</td>
<td>Moderate</td>
<td>*</td>
<td>*</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>Moderate</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>13</td>
<td>Moderate</td>
<td>-</td>
<td>*</td>
<td>-</td>
</tr>
</tbody>
</table>
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In Table 5.2a-c, Day 1 is the occurrence day of the storm. The category A storms had the main phase in the daytime of Day 1, category B had the main phase in the pre-midnight of Day 1 and category C storms had their main phase in post-midnight of Day 1. The Day 0 is one day before the storm day while Day 2 is the day after the storm occurrence. It is seen from Table 5.2a that in the case of category A storms, mostly weak scintillation events are recorded on the Day 1, in the daytime and post-midnight events in the early morning of Day 2. There were no scintillations during pre-midnight of Day 0, indicating the suppression of scintillation occurrence in the pre-midnight on the day of the main phase of the storm. The pre-midnight scintillation events seem to be reduced. Bhattacharya et al. [2002] studied storm-time VHF (244 MHz) scintillations using data recorded at Ancon (11.8° S), USA, and found that scintillations in category A storms began after sunset and lasted till post-midnight period. Aarons et al. [1997] studied two storms of this category with GPS scintillation data recorded at Santiago (33° S), Chile, Arequipa (16° S), Peru and Bogota (15° N), Colombia around the magnetic equator; first one on 2-5 April 1994 for which they found amplitude scintillations of high intensity in the pre-midnight period, for the second magnetic storm of 24 September to 2 October 1995, they recorded scintillations on 24 September in the pre-midnight period from 16:00 to 20:00 LT.

As shown in Table 5.2b, under category B storms moderate to strong scintillations were recorded in the daytime of Day 1 with weak events on Day 2 pre-midnight. In addition, both weak and moderate scintillations were recorded before the main phase of the storm day. However, an extraordinary storm effect was recorded for Storm 17, with moderate intensity. This storm initiated moderate scintillations on the daytime of storm day, weak in the pre-midnight and moderate to strong events on the Day 1. This then died out as the storm proceeded into the recovery phase. Effect of category B storm on 22 October 1999 was studied by Bhattacharya et al. [2002] and they found VHF (244 MHz) scintillation occurrence after sunset on the storm day which lasted just after 23:00 LT.

In category C storms (Table 5.2c), the results varied from very few scintillation occurrences on the onset day and a little on the day after it. Most storms showed scintillation occurrences on Day 2, after the storm which is in the recovery phase of the
storm. Aarons et al. [1997] studied the effect of a category C storm on 2-7 November 1993 with onset on 3 November at Kourou (5° N), French Guinea and Santiago (33° S), Chile. They found GPS scintillation of high intensity near sunset and in the post-midnight period on 4 November and no scintillations on 5-6 November. Bhattyacharya et al. [2010] also studied GPS scintillation at Bhopal (23.2° N), India, under a category C storm on 21 January 2005. They observed the scintillations only on 22 January 2005 after 20:30 LT. Priyadarshni and Singh [2011] studied effect of this category of storm that occurred on 3-4 August 2010, on GPS scintillations at Varanasi, (23.5° N), India. There were two minimum Dst occurrences; one at 04:30 LT (-62 nT) and the other at 09:30 LT (-65 nT) on 4 August. During the main phase of the storm, GPS scintillations between 23:30 LT and 07:30 LT on 4 August 2010 were suppressed. They suggested that geomagnetic activity suppresses GPS scintillations if main phase occurs in the post-midnight.

In the present work, out of 17 storms 14 were moderate and 3 intense. The moderate storms of any category, as seen from Tables 5.2a-c, do not show any clear effect on the occurrence of scintillations. There seems to be suppression of scintillation in the pre-midnight of Day-0 and no effect on Day-1 and 2. Kumar and Gwal [2000] from the intense storm effect on VHF scintillations at Bhopal, India, found that when that main phase of storms occurred in the post-midnight (category C) the occurrence of scintillations was enhanced in post-midnight period which extended into daytime. However, there were no intense storms under category C during the period of our study.

Thus overall it seems that the scintillation occurrences are still unpredictable since it displays varied behavior in all the storms. More data on storms is needed to investigate the effect of storms on scintillation at Suva. The coming phase solar cycle may give sufficient number of storms under each category to draw clear conclusion. However, scintillation occurrence on the storm onset seems to be related to the prompt penetration of the storm-time electric field to mid and low latitudes. A number of studies have been carried out which explain the development or inhibition of ESF during geomagnetic storm and the role of storm-time electric fields perturbations [e.g. Fejer et al., 1999 and Basu et al., 2007] and disturbance dynamo electric-field.
5.2.3 Geomagnetic disturbance effect on TEC

To examine the geomagnetic storm effect on TEC at Suva, VTEC on five quiet (Q) and five disturbed (D) days of each month of 2010 were separated and then the averages and the standard deviations (SD) from the mean were calculated to indicate the variability of VTEC on Q- and D-days. The mean VTEC and SD are shown in Figure 5.3a and 5.3b for January-June and July-December, respectively. Excluding January (since only one Q-day data was available) and February (since no Q-days data were available), it is clear that for all the other months VTEC is higher on D-days as compared to Q-days, particularly in the daytime. The VTEC values start rising over Q-day values in morning time between 06:00-10:00 LT with peak difference at around 12:00-14:00 LT. With that, when the variability of VTEC from the mean is compared using SD on Q- and D-days it is found that variability is larger on D-days with maximum SD at 12:00-14:00 LT.

Table 5.3: Percentage SD for Q- and D-days during pre-midnight, daytime, post-midnight for each month of 2010.

<table>
<thead>
<tr>
<th>Months</th>
<th>Pre-midnight</th>
<th>Daytime</th>
<th>Post-midnight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Q-days (%)</td>
<td>D-days (%)</td>
<td>Q-days (%)</td>
</tr>
<tr>
<td>January</td>
<td>No-data</td>
<td>2.0</td>
<td>No-data</td>
</tr>
<tr>
<td>February</td>
<td>No-data</td>
<td>7.1</td>
<td>No-data</td>
</tr>
<tr>
<td>March</td>
<td>2.3</td>
<td>1.4</td>
<td>5.3</td>
</tr>
<tr>
<td>April</td>
<td>1.3</td>
<td>1.7</td>
<td>1.0</td>
</tr>
<tr>
<td>May</td>
<td>0.8</td>
<td>1.0</td>
<td>0.9</td>
</tr>
<tr>
<td>June</td>
<td>1.3</td>
<td>1.8</td>
<td>0.7</td>
</tr>
<tr>
<td>July</td>
<td>1.0</td>
<td>1.6</td>
<td>0.1</td>
</tr>
<tr>
<td>August</td>
<td>1.5</td>
<td>2.3</td>
<td>2.7</td>
</tr>
<tr>
<td>September</td>
<td>1.9</td>
<td>1.3</td>
<td>2.2</td>
</tr>
<tr>
<td>October</td>
<td>1.1</td>
<td>1.6</td>
<td>6.4</td>
</tr>
<tr>
<td>November</td>
<td>2.9</td>
<td>1.3</td>
<td>4.4</td>
</tr>
<tr>
<td>December</td>
<td>1.1</td>
<td>2.8</td>
<td>3.8</td>
</tr>
</tbody>
</table>
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Figure 5.3a: VTEC on quiet (Q) and disturbed (D) days with standard deviation for the months of January 2010 to June 2010.
Figure 5.3b: VTEC on quiet (Q) and disturbed (D) days with standard deviation for the months of July 2010 to December 2010.
In order to quantify the geomagnetic disturbance on VTEC in the post-midnight, daytime and pre-midnight periods, on monthly basis, the percentage SD about the respective means are presented here at these specific times; 05:00 LT, 14:00 LT and 22:00 LT. The percentage SDs for pre-midnight Q- and D-days, daytime Q- and D-days and the post-midnight Q- and D-days are shown in Table 5.3. Overall, the Q-day percentage SD in the pre-midnight is 1.52%, daytime is 2.75%, and in the post-midnight is 2.16%. While the D-days percentage SD in the pre-midnight is 2.16%, daytime is 5.4% and post-midnight is 2.75%.

The D-days variability has been attributed to the geomagnetic activity that perturbs the homogeneity of the ionosphere, however, variability on the Q-day also occurs but lacks considerable understanding. Rishbeth and Mendillo [2001] studied the day-to-day variability of F2-layer and found that the peak electron density of the ionosphere varies from day-to-day with a standard deviation of about 20% by day and 33% by night, while in our case it is somewhat different, however, the results are in agreement with findings from the Indian low latitude region [e.g. Bagiya et al., 2009 (Rajkot- 22.29° N); Chauhan et al., 2011 (Agra- 27.12° N); Kumar and Singh, 2009 (Varanasi- 25.28° N); Dabas et al., 2006 (Dehli- 28.6° N)], whereby their results show higher daytime variability as compared to nighttime.

As the monthly Q- and D-days’ variability is combined to examine the seasonal geomagnetic effects on the ionosphere, it is generally seen that during hot and wet season, the VTEC is higher compared to the cold and dry season and with that the variability is also greater in this season as shown in Figure 5.4(a, b).

Though during hot and wet season the VTEC on D-days is higher, the Q- and D-days variability (SD) is almost equal throughout the daytime, pre- and post-midnight periods. On both Q- and D-days, the daytime variability is higher, followed by pre-midnight and least during the post-midnight period. During cold and dry season, the VTEC as well as the variability on D-days is higher than on Q-days. The daytime variability on both Q- and D-days is the highest followed by pre-midnight and lowest variability is in the post-midnight period. To observe the overall variability on Q- and D-days of 2010, the annual plot of diurnal TEC variation is in Figure 5.5. The annual data also reveals higher VTEC on D-days as compared to Q-days. The variability in the
daytime is maximum and is higher for D-days in comparison to Q-days. Followed by is the variability in the pre-midnight period and during this time the Q- and D-days show almost same variability. The lowest variability is seen in the post-midnight period with D-days having higher variability than Q-days. Overall, the D-days VTEC as well as the variability is higher with maximum variability in the daytime.

**Figure 5.4:** Seasonal variation of VTEC on quiet (Q) and disturbed (D) days with standard deviation during 2010. a) Hot and wet season. b) Cold and dry season.
Day-to-day variability is of great importance in the development of empirical ionospheric models. The day-to-day variability is found to be greater in the region of EIA and at high latitudes and has been attributed to solar and geomagnetic and other causes [Fuller-Rowell et al., 2002]. These other causes/influences were termed by Rishbeth and Mendillo [2001] as meteorological factors and they seemed to radiate from the lower part of the atmosphere. Lastovicka [2005] studied these meteorological factors and found that processes such as planetary waves, gravity waves and tides have direct or indirect effect on the F-region and thus induce variations in TEC. In addition, the ionosphere in the EIA region is also affected by the electrodynamics’ coupling between the thermosphere and the ionosphere known as penetrating electric field and it is difficult to separate the effects of geomagnetic activity and the meteorological influence, especially during high solar activity years, since such activities do not allow ample time for the upper atmosphere to return to its quiescent state [Zhao et al., 2008].

Figure 5.5: Annual variation of VTEC on quiet (Q) and disturbed (D) days with standard deviation during 2010.
The ionospheric electric fields could also increase the VTEC on disturbed days. The principal sources of electric fields in the ionosphere are generally due to the circulation of the neutral atmosphere across the Earth’s magnetic field under the influence of tidal winds (ionospheric wind dynamo) and the convection of magnetospheric plasma due to dynamical interaction between solar wind and the magnetosphere (solar wind-magnetosphere dynamo) [Sastri, 1988]. Any geomagnetic activity conditions by perturbations in the solar wind-magnetospheric dynamo and ionospheric wind dynamo can alter the global distribution of ionospheric currents and electric fields. The geomagnetic activity related disturbances in the equatorial zonal electric field/currents are broadly classified into two groups depending on their nature and duration (rapid changes of short duration or slow varying and persistent changes) and on the time delay of their appearance and reference to causative geomagnetic disturbance (prompt or delayed effects) [Sastri et al., 1997]. Short-lived (≈ 2 hour duration) electric field perturbations often occur in close temporal association with auroral substorm and symmetric/asymmetric ring current activities. Persistent (several hours duration) and slow varying electric field disturbances follow the onset of magnetic storms/substorms with long delays (> 6 h) with polarity opposite to the quiet-time electric field patterns at practically all local times [Sastri, 1988]. During magnetically active times, a fraction of dawn-dusk electric field can penetrate spontaneously to the low latitudes via current leakage, yielding an eastward electric field on the dayside and a westward on the night side [Lu et al., 2012]. During daytime this lifts the plasma to higher altitudes whereby, the ratio of production to loss is larger at higher altitudes resulting in enhancement in electron densities in the dayside sector, while an opposite is often expected on the night-side sector. Large enhancement in TEC and intensification of EIA, in the dayside sector of the ionosphere has been found by many workers [e.g. Maruyama et al., 2005; Lin et al., 2005 and Zhao et al., 2008] and they suggested that prompt penetration of electric field is the significant contributor during disturbed days. The dynamics of the neutral wind and the equatorial electrojet (EEJ) strength also brings about the variability in TEC [RamaRao et al., 2006a]. The neutral winds are driven by external sources usually attributed to the Joule heating and largely depend upon the distribution of the energy sources in altitude, latitude and
longitude [Heelis, 2004]. Maute et al. [2012] used NCAR TIME-GCM model to simulate and investigate the factors affecting the $\mathbf{E} \times \mathbf{B}$ drift and found that neutral winds at all latitudes are the main contributor to $\mathbf{E} \times \mathbf{B}$ drift. The $\mathbf{E} \times \mathbf{B}$ drift is also dependent on the equatorial electrodynamics modulated by equatorial electrojet (EEJ) and counter electrojet events (CEJ) [Hajra et al., 2012]. The EEJ is produced by the daytime dynamo electric field in the presence of the horizontal magnetic field at the dip equator. At times the EEJ current reverses from eastward to westward during morning and afternoon hours and even on magnetically quiet days and is known as CEJ. A good correspondence is noted between EEJ strength and daytime $\mathbf{E} \times \mathbf{B}$ plasma drift at magnetic equator [Hajra et al., 2012]. On CEJ days, weakening or disappearance of fountain effect leading to perturbations in EIA has been reported. Sripathi and Bhattacharyya [2012] asserted that EEJ are generated by atmospheric tides through dynamo action, therefore, any modulation of E-region winds by planetary waves would produce oscillations in EEJ and subsequently the strength of EIA. Dabas et al. [2006] studied F-region variability at Thiruvanthapuram (8.5° N), Kodaikanal (10.2° N) and Delhi (28.6° N) during 1970 and 2001, a high solar activity period and found that variations in daytime $f_0F_2$ were not related to solar and magnetic activity changes, but were controlled by EEJ strength variations and they considered the perturbations in electric fields and thermospheric winds as the main cause of day-to-day variability, since these produce fluctuations in the E- and F-layers. Sastri [1998] reported large and sudden increases in the height of the bottom side of F-layer ($h’F$) from 53 to 117 km in the post-sunset period during 1957-1969. He found height increase on eight magnetically quiet days with ($Ap \leq 5$) and attributed this to the post-noon enhancement of the equatorial electrojet (EEJ) and intensification of EIA. All these contribute to higher day-to-day variability on D-days as compared to Q-days.

Wang et al. [2008] studied the relationship between geomagnetic activity ($Dst$) with TEC using data recorded between 12:00-13:00 LT, at Ancon (11.78° S), Peru during March 1998-August 1999, and found that the correlation between TEC and geomagnetic activity increases with geomagnetic activity. They also unexpectedly found the correlation above the 95% confidence level (by ~0.05) at 2-3 day periods even during quiet days, indicating that even low levels of geomagnetic activity have
measurable effect on equatorial TEC. They attributed this persistence of the correlations (increase in TEC with magnetic activity) to planetary waves and atmospheric waves as these would force the ions and consequently affect the ionosphere. Karia and Pathak [2011] studied TEC variation with $Dst$ using data collected at Surat ($21.16^\circ$ N), India, during 2011. They found that with $Dst < -50$ nT, the TEC increased and observed that the O/N$_2$ decreased at high latitudes and enhanced at lower latitudes using the TIME/GUVI image. They attributed the higher values of TEC to the high ionization density due to the increased production rates (indicated by O/N$_2$ ratio). The GPS receiver measures the TEC which is an integrated electron density from the D, E, F and topside regions. Since the F-layer contains the highest concentration of electrons any variations in this could account for large day-to-day variability in TEC. The possible causes of F-layer variability includes; solar ionizing radiations, solar wind and geomagnetic activity, neutral atmosphere and the electrodynamics. Through this study it was found that in the daytime period, TEC variability on D-days was the highest. Rishbeth and Mendillo [2001] suggested that TEC variability is due to three factors; solar (3%), geomagnetic sources (15-20%), and meteorological sources (15-20%). On Q-days there is no geomagnetic activity effect so the variability is lesser by 15-20% when compared to D-days. The large day-to-day variations in F-layer on geomagnetic active days are due to variability in the neutral winds that give rise to the electric field of the dynamo region [Chandra et al., 2009]. During geomagnetic active periods, the effects on F-layer could be due to changes in the electric field (DD) or due to changes in thermospheric neutral composition. The nature and strength of the effect of magnetic disturbances on plasma is found to be different for different magnetically disturbed days, which may be attributed to differences in the magnetic activity level on those days, and hence in Joule energy, and the starting time and duration of magnetic activity [Engavale et al., 2006]. Zhao et al. [2008] studied Q-day variability using 70 GPS receivers around the Asian-Australian sector and suggested that extremely large day-to-day variability is caused by the combination of auroral activity and a disturbance originated in the lower atmosphere. In addition, the direct energy coupling between strong lightning discharges can cause short-term (10-200s) changes in the electron density or conductivity at the lower ionosphere [Rodger, 2003] thus, can also contribute
to day-to-day variability mainly at the low latitudes. The heating of lower ionosphere by strong quasi-electrostatic (QE) field generated by strong lightning causes the conductivity/electron density enhancements. Such strong QE electric field in the low latitude can penetrate to F-region and change F-region plasma drift (or electric field, since \( v = \mathbf{E} \times \mathbf{B} / B^2 \)) and hence the fountain effect. Strong lightning associated with thunderstorms are also a major source of atmospheric gravity waves (AGWs) which propagate to great heights and affect the motion and density of plasma in the F-region ionosphere [Kumar et al., 2009]. Ramachandran et al. [2005] studied the strong lightning (> 50 kA) detected by the World-Wide Lightning Location Network for Fiji and found that lightning activity is significantly enhanced between 12:00-17:00 LT with maximum at around 14:00 LT which is the time of maximum day-to-day variability in the VTEC at Suva.

Thus, Q-day variability at low latitudes can be related to changes in solar flux, the fountain effect and equatorial electrojet currents as well as the meteorological factors. The increased variability on D-days as compared to Q-days can be accounted by the planetary waves, increased auroral activity, DD electric field and changes in thermospheric neutral composition as the enhancement of O/N\(_2\) ratio occurs at lower latitudes.

**5.2.4 TEC variation during geomagnetic storms**

To investigate TEC variation during geomagnetic storms, the VTEC was examined during the main phase and recovery phase of the storms with background level. The background level was the average of VTEC on five international magnetically quiet (Q) days of the respective months in which storm occurred. When the storm VTEC was compared with the background VTEC, the day-to-day variability was taken into consideration. This implies that a TEC enhancement (reduction) occurred if there was an increase (decrease) in VTEC above (below) this variability (tolerance) level with respect to the background level during the storm. The effect of the 17 storms given in Table 5.1 categorized under category A, B and C was examined during main phase and recovery phase of the storms. The results are shown in Tables 5.4a-c.
The daytime Q-days’ variability about the mean in March was 5.3%, April 1.0%, May 0.9%, June 0.7%, July 0.1%, August 2.7%, September 2.2%, October 6.4%, November 4.4% and December 3.8%. Since no data for Q-days were available for January and February, the variability of these months was taken as mean variability on Q-days for above months. The storms were categorized into category A, B and C as described in section 2.2.3 and then the TEC variation under each category storm was examined as shown in Table 5.4a-c.

Table 5.4a: Variation of VTEC during category A storms in 2010 and 2011, as given in Table 5.2a.

<table>
<thead>
<tr>
<th>Storm No.</th>
<th>Storm Strength</th>
<th>Effect on VTEC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Main Phase</td>
</tr>
<tr>
<td>2</td>
<td>Moderate</td>
<td>No Change</td>
</tr>
<tr>
<td>8</td>
<td>Moderate</td>
<td>No Change</td>
</tr>
<tr>
<td>10</td>
<td>Moderate</td>
<td>Increase</td>
</tr>
<tr>
<td>11</td>
<td>Moderate</td>
<td>Increase</td>
</tr>
<tr>
<td>12</td>
<td>Intense</td>
<td>Increase</td>
</tr>
<tr>
<td>15</td>
<td>Intense</td>
<td>Increase</td>
</tr>
<tr>
<td>16</td>
<td>Intense</td>
<td>Increase</td>
</tr>
</tbody>
</table>

Table 5.4b: Variation of VTEC during category B storms in 2010 and 2011, as given in Table 5.2b.

<table>
<thead>
<tr>
<th>Storm No.</th>
<th>Storm Strength</th>
<th>Effect on VTEC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Main Phase</td>
</tr>
<tr>
<td>4</td>
<td>Moderate</td>
<td>No Change</td>
</tr>
<tr>
<td>15</td>
<td>Moderate</td>
<td>Increase</td>
</tr>
<tr>
<td>17</td>
<td>Moderate</td>
<td>Increase</td>
</tr>
</tbody>
</table>

Table 5.4c: Variation of VTEC during category C storms in 2010 and 2011, as given in Table 5.2c.

<table>
<thead>
<tr>
<th>Storm No.</th>
<th>Storm Strength</th>
<th>Effect on VTEC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Main Phase</td>
</tr>
<tr>
<td>1</td>
<td>Moderate</td>
<td>Increase</td>
</tr>
<tr>
<td>3</td>
<td>Moderate</td>
<td>Increase</td>
</tr>
<tr>
<td>5 &amp; 6</td>
<td>Moderate</td>
<td>Increase</td>
</tr>
<tr>
<td>7</td>
<td>Moderate</td>
<td>Decrease</td>
</tr>
<tr>
<td>9</td>
<td>Moderate</td>
<td>Decrease</td>
</tr>
<tr>
<td>13</td>
<td>Moderate</td>
<td>Increase</td>
</tr>
</tbody>
</table>
Considering category A storms of which the main phase occurs in the daytime, in most of the storms (5 out of 7) the VTEC increased during the main phase of the storms. In remaining two cases there were increases but within the range of quiet days’ variability. During the recovery phase of these category storms, the VTEC was higher except for one storm whereby a decrease in VTEC was found with respect to the quiet days mean. Pandey and Dashora [2006] studied the effect of two storms of this category on TEC at Udaipur (24.58° N), India. For the first storm on 7-11 November 2004, they found that during the main phase the VTEC reduced by 30% and then increased by almost 25% during the recovery phase of the storm. For the 13-17 May 2005 storm, they found that the VTEC was lower before and after the main phase on 14, 17 and 18 May with considerable enhancement during the main phase of the storm. Dashora and Pandey [2007] further analyzed the TEC variations for great geomagnetic storm of 7 November 2004 (\(Dst = -373\) nT) and found that during the main phase on November 8 between 10:30-13:30 LT, VTEC was lower by 15 TECU when compared to mean VTEC and consistently lower than mean between 13:30-16:30 LT and attributed this reduction to the disturbance dynamo fields that damped the development of the EIA enhancement. Jain et al. [2010] studied the effect of two very intense storms of this category on TEC at a low latitude station Bhopal (23.2° N), India. The first storm occurred on 15 May 2005 (\(Dst = -247\) nT) and they found that there was about 68% increase in VTEC, three hours after the onset of the main phase of the storm. The other storm occurred on 24 August 2005 (\(Dst = -184\) nT) whereby two enhanced anomaly peaks were formed during the main phase; one around 17:00 LT and the other around 18:30 LT and both peaks showed increase of TEC by 70%. Bagiya et al. [2009] studied TEC at Rajkot (22.29° N), India, for intense geomagnetic storm of August 24, 2005 (\(Dst = -184\) nT). They found that TEC increased by 20 TECU on August 24 (main phase) with respect to average quiet days’ value and decreased by 18 TECU on August 25 (recovery phase). The increase in TEC during main phase of category A storms (Table 5.4a) indicates the prompt penetration (PP) of high latitude electric field to low latitude of Fiji, enhancing the ionospheric \(E\) and hence the \(E \times B\) drift i.e. EIA. For such storm recovery phase falls in the nighttime and by this time storm time disturbance
electric field will affect the ionospheric $E$ and reduce the nighttime downwards $E \times B$ drift which would enhance TEC.

In category B storms (Table 5.4b) the increase in VTEC during the main phase was more profound (2 out of 3) while the recovery phase showed disparity, whereby storm No. 4 showed no change, storm No. 15 showed increase and storm No. 17 showed a decrease. Yizengaw and Essex [1999] studied TEC effect of a category B storm that occurred on 22-24 September 1999 at four stations Townsville (19.6° S), Tidbinbilla (35.4° S), Hobart (42.8° S) and Macquarie Island (77.8° S) in Australia. They found that at the mid-latitudes (Tidbinbilla and Hobart) the TEC decreased while at the high-latitude (Macquarie Island) and the low latitude station (Townsville) an increase in TEC was observed during the main phase of the storm.

The category C storms showed varying results. Out of seven storms, five showed an increase in VTEC while two showed a decrease in the main phase of the storm. During the recovery phase three showed an increase in VTEC while four showed no change. A category C storm was studied by Wu et al. [1997] that occurred on 10 January 1997, over Taiwan in the EIA region. They found that during the main phase which occurred in the post-midnight, the VTEC increased from the average quite time of 21.14 to 26.3 TECU.

It has been known that during geomagnetically disturbed conditions, ionospheric electric fields and currents at low latitudes are altered by the direct prompt penetration of a dawn-dusk electric field to equatorial and low latitude ionosphere [Fejer et al., 1999; Bagiya et al., 2009]. This electric field perturbation during magnetic storms usually affects the distribution of ionospheric plasma. As a result, the outcome is either a positive ionospheric storm (with increased electron density) or a negative ionospheric storm (with decreased electron density) at low latitudes [Basu et al., 2001]. The prompt penetration of solar wind electric fields directly to low latitudes is short lived ($\approx$ 2 hour duration) [Sastri et al., 1997]. This prompt penetration of electric fields occurs during sudden commencement whereby sudden changes in the dynamic wind pressure occur. This generates a dawn-dusk electric field in the equatorial ionosphere which is eastward in the day-side and westward in the night-side. On the day-side sector, this prompt penetrating eastward electric field associated with large and sudden increase in the high
latitude convection increases the upward drift velocities of ionosphere [Fejer et al., 1999]. This lifts the plasma to higher altitudes. Since, the ratio of production to loss is larger at higher altitudes, enhancement in the electron densities in the dayside sector occurs. Maruyama et al. [2005] found huge enhancement in TEC in the dayside sector of the ionosphere and suggested that prompt penetration electric field is the significant contributor. Thus, an opposite is often expected on the night-side sector as depletion in TEC. In addition, Lin et al. [2005] and Zhao et al. [2008] found that in association with the prompt penetration electric field, the EIA has been observed to intensify in peak TEC as well as in latitudinal coverage.

On the other hand, the high energy solar wind deposits highly energized particles into the polar cusps. These energized particles diffuse slowly from the high latitude to the low latitude region with time scales varying from several hours to days resulting in disturbance dynamo (DD) electric field. This DD electric field perturbs the low latitude electric fields and currents generally during the recovery phase of the geomagnetic storm as well as up to about a day or two after the onset. The DD electric field perturbations are westward (eastward) in the dayside (night-side) sector which is opposite to the daytime (nighttime) ionospheric dynamo electric field. Thus, this opposing electric field causes depletion of TEC in the dayside sector forming negative ionospheric storms and suppression of EIA peaks, while F-layer uplift and intensification of EIA results in the night-side sector [Fuller-Rowell et al., 2002].

The particle precipitation in the auroral cusps maximizes the energy exchange in the E-region between the plasma and the neutral particles which results in substantial frictional or Joule heating [Lu et al., 2012]. This rapid heating at high latitudes causes the expansion of neutral atmosphere resulting in increased auroral electrojet and thus the generation of acoustic gravity waves (AGWs) follows. This in turn modifies the global thermospheric circulation due to pressure gradients and an enhanced equatorward wind develops and when the heating events are spontaneous this often takes the form of equator-ward surges known as Traveling Atmospheric Disturbances (TADs) [Buosanto, 1999]. These TADs can penetrate to low latitude and even to the opposite hemisphere. In the ionosphere these are patented as travelling ionospheric disturbances (TIDs). As these waves propagate towards the equator, redistribution of energy through
viscous interaction, heat conduction and frictional loss due to ion drag occurs with a time delay of a day or more [Fuller-Rowell et al., 2002]. Considering the particle masses, the atomic particles like O ions are lighter in comparison to molecular varieties like O₂ and N₂. Therefore, the lighter ones lifts up first and gets transported to the low latitudes before the heavier ones resulting in negative ionospheric storms. After a storm, the meridional wind direction and magnitude also changes. In particular, in the daytime the meridional winds are found to be pole-ward while during the night-time this reverses. However, following a storm the wind flows from the poles to the equator region during the daytime and further alters the quiescent state of the ionosphere. Thus, a storm can bring about either positive or negative condition depending on the PP electric field, DD electric field as well as the changes in the meridional winds.

The case studies of three geomagnetic storm effect on TEC at Suva are presented in the following section. The storms are from each of the categories (A, B, C) as described before.

5.2.5 Geomagnetic storm effects: case studies

a) Storm of 26-28 September 2011: The variation of $Dst$, TEC and TEC on Q-days under this storm selected from category A, is shown in Figure 5.6.

![Figure 5.6: TEC variation under category A storm of 26-28 September 2011. The storm VTEC and Q-day VTEC have been plotted for comparison. Panel a) shows $Dst$ and b) shows storm and Q-days VTEC.](image-url)
This was an intense storm of SGC type with commencement at around 00:00 LT on 27 September and $DST$ index reaching a minimum of -103 NT at 12:00 LT on 27 September. During this storm there was a pre-storm enhancement in VTEC on 26 September with maximum of 13 TECU (15.8%) at 17:00 LT, on the storm day and during the main phase of VTEC enhanced with maximum of 18 TECU (22.9%) at 11:00 LT. Recovery phase showed an enormous enhancement in VTEC with maximum of 35 TECU (43.3%) at 14:00 LT. These enhancements were with respect to the mean Q-days VTEC for the month of September with 2.2% of variability for this month.

b) Storm of 1-4 November 2011: This was a category B storm with moderate intensity as shown in Figure 5.7. It is classified as SGC type with commencement at around 06:00 LT on 1 November and minimum $Dst$ of -61 nT at 04:00 LT. VTEC increased by about 13 TECU (10%) was recorded at 17:00 LT during the main phase of this storm. As the minimum $Dst$ value was achieved, the VTEC decreased by 8 TECU (6.1%) with respect to the mean on 2 November and a further decrease of about 21 TECU (15.1%) was recorded on 3 November and 17 TECU (13%) on 4 November, during the recovery phase of the storm.

![Figure 5.7: TEC variation under category B storm of 31 October-4 November 2011. The storm VTEC and Q-day VTEC have been plotted for comparison. Panel a) shows $Dst$ and b) shows storm and Q-days VTEC.](image-url)
c) Storm of 2-5 May 2010: This was a category C storm of SSC type with SSC at 21:08 LT on 2 May as shown in Figure 5.8. The intensity of the storm was moderate with minimum $Dst$ of -67 nT at 06:00 LT on 3 May. This particular storm had a very slow recovery phase. During the pre-storm time the VTEC was within the variability range of 0.9% about the mean. However, during the main phase the VTEC increased to 10 TECU (13.3%) at 18:00 LT on 3 May from the mean. During the recovery phase as the $Dst$ index decreased the VTEC also decreased. On November 4 the increase was of only 3 TECU (4.9%) and on November 5 the VTEC returned to its normal value.

![Figure 5.8: TEC variation under category B storm of 2-5 May 2010. The storm VTEC and Q-day VTEC have been plotted for comparison. Panel a) shows $Dst$ and b) shows storm and Q-day VTEC.](image)

### 5.3 Conclusions

A comprehensive investigation was carried out on the magnetic activity effect on the low latitude ionosphere specially the scintillations and VTEC. The main results of this study can be concluded as follows:

- The percentage occurrence (frequency), the number of events (periodicity) as well as the strength of scintillation, in general, increases on the magnetically D-days when compared to D-days. Mostly weak amplitude scintillation events of
duration greater than 3 minutes were recorded during 2010 and 2011 which can be attributed to small scale irregularities.

- Generally, all the three category (A, B and C) of storms showed post-storm scintillations on the days following the storm which indicates the storm generation of ESF. However, some category C storms showed pre-storm scintillations. Further, investigation during high solar activity could give a clearer picture.

- The daytime variability in VTEC is higher on the D-days as compared to Q-day during all the months except August and October. The months of August and October showed less daytime D-days’ TEC variability as compared to Q-days’ variability. The higher variability during magnetically disturbed condition is attributed to geomagnetic disturbances- prompt penetration and disturbance dynamo electric field which perturb the homogeneity of the ionosphere. Variability on the quiet day can be related to changes in solar flux, equatorial electrojet currents, fountain effect and the meteorological influences.

- The storm-time ionospheric perturbations due to either prompt penetrating electric field or the disturbance dynamo electric field and storm induced change in thermospheric composition leads to positive (increase in VTEC) or negative ionospheric storms (decrease in VTEC), respectively. For category A storms, TEC increase was found mostly in both the main and recovery phases. For category B storms, increase in VTEC during the main phase was found, however, during recovery phase the VTEC either increased or decreased. While, for category C storms, contrasting results were found since some storms increased the VTEC in the main phase while others decreased. However, in the recovery phase about 42.9% (3 out of 7) of storms showed an increase and rest 57.1% (4 out of 7) showed no change in VTEC.
Chapter 6  
Summary and Future Scope of Work

6.1 Summary

This dissertation deals with GPS based total electron content (TEC) and GPS L1-band scintillations recorded during 2010, at Suva, a low latitude station near the crest of southern anomaly. The period of observation falls into low solar activity year of current (24) solar cycle. The slant total electron content (STEC) and scintillation index \( S_4 \) are recorded using state of art (GSV 4004B) receiver. The observations made from January 2010 to December 2011 at Suva have been utilized to study the diurnal, monthly, seasonal and annual TEC and scintillation variations as well as the storm effects on TEC and scintillations. The receiver records data in terms of GPS time and week. The data recorded by GSV 4004B receiver was then sorted and truncated from GPS weeks to make it par with the Gregorian calendar and local time. The rows with data having a LockTime at L1 and L2 for less than 240 seconds were eliminated and further smoothing was done by eliminating data with very large sigma phase (60 sec sigma phase) values. The data with elevation angle less than 50° were also eliminated. The STEC was converted to VTEC for uniformity and to remove the biases induced by elevation angles. The VTEC data was then imported to Matlab and smoothed using the CSAPS toolbox utility. Diurnal TEC variation showed a minima at around 02:00-06:00 LT with a peak at around 14:00 LT. Larger day-to-day variability in TEC was recorded in daytime as compared to the pre- and post-midnight periods with larger day-to-day variability in hot and wet season than cold and dry season. Seasonal TEC also showed higher values in hot and wet season with maxima in December (summer solstice) and minimum in June (winter solstice). To study amplitude scintillations, the corrections to \( S_4 \) were subtracted from the recorded \( S_4 \) to compute the Final \( S_4 \) (\( S_4 \) Fin). Then the diurnal, monthly, seasonal and annual scintillation variations were obtained with scintillations being classified into weak, moderate and strong based on the intensity of \( S_4 \). L-band amplitude scintillations showed higher occurrence in the daytime as compared to the nighttime period. The weak scintillation events were most common (84.4%, 405 out of 480 events) followed by moderate (14.6%, 70 out of 480 events) and
only 1% (5 out of 480 events) of strong events were recorded. A higher percentage of scintillation occurrences were recorded in hot and wet season (59%, 284 out of 480) compared to cold and dry season (41%, 196 out of 480). Annual variation showed 71% (338 out of 480) of daytime events, 15% (74 out of 480) of pre-midnight events and 14% (68 out of 480) of post-midnight events. Phase scintillations and TEC fluctuations did occur with post-midnight strong amplitude scintillation events but not in the cases of daytime strong scintillation events. The SSC and \( Dst \) index were attained from the NGDC and WDC, respectively. This was done to study the effect of different category (A, B, C) and varying strength (moderate, intense and very intense) geomagnetic storms on TEC and scintillations. On the magnetically disturbed days the percentage occurrence, the number of events and the strength of scintillations was found to increase as compared to quiet days. During geomagnetic storms of all categories (A, B and C) the post-storm scintillation events were mostly recorded. The daytime variability in VTEC is also found to increase on the D-days as compared to Q-days during all the months except August and October where Q-days variability was greater. The storms were categorized before studying their effect on TEC and it was found that for category A storms (7 storms), TEC increase occurred in both the main and recovery phases. For category B storms (3 storms), increase in VTEC during the main phase was found, however, during recovery phase the VTEC either increased or decreased. The category C storms (7 storms), in the main phase, 71.4% (5 out of 7) storms showed increased VTEC while 28.6% (3 out of 7) showed a decrease. The recovery phase of category C storms, 42.9% (3 out of 7) showed an increase and 57.1% (4 out of 7) showed no change in VTEC.

### 6.2 Future Scope of the Work

- Scintillation studies of the L-band are very limited especially in the South Pacific region. The present investigation deals with scintillation study during 2010 only. Long-term scintillation measurements at this frequency at our station will be useful in understanding the morphology of scintillations at low latitude and in addressing the issues on improving the accuracy of GPS positioning. Daytime scintillation reports on L-band are very limited. The occurrence of
daytime scintillation in this work forms a good basis for further investigations on irregularity formations in the daytime ionosphere. More data on L-band scintillation using a chain of global GPS receivers can give clearer picture of latitudinal and longitudinal variation of scintillation activity.

- From the geomagnetic storm effect point of view, this work can be extended to higher solar activity phase of current solar cycle for: i) better understanding of the equatorial and low latitude ionosphere-thermosphere system coupling during the geomagnetic storm. ii) to find out the role of neutral composition variation under positive and negative ionospheric storms during the geomagnetic storm conditions.

- Solar flare effects on TEC could also be studied. With that quantitative relation could be found between a solar flare and the ionospheric variations.

- The spectral properties and the dynamics of ionospheric irregularities causing GPS L1-band scintillations could be studied using Fast Fourier Transforms (FFT i.e. power spectrum) and Wavelet spectrum.
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Annexure I

The functions of cubic spline toolbox used in data analysis.

```matlab
if nargin<3||isempty(p), p = end
if nargin<4, xx = [] end
if nargin<5, w = [] end
ifiscell(x)
    m = length(x)
sizey = size(y)
    if length(sizey)<m error('SPLINES:CSAPS:toofewdims',...
        ['If X is a cell-array of length m, then Y must have', ...'
        ' at least m dimensions.']) end
end
if length(sizey)==m,
    ifissparse(y), y = full(y) end
    sizey = [1 sizey]
end
sizeval = sizey(1:end-m) sizey = [prod(sizeval), sizey(end-m+(1:m))]
y = reshape(y, sizey)
if ~iscell(p)
    if length(p)~=m, p = repmat(p(1),1,m) end
    p = num2cell(p)
end
ifisempty(w), w = cell(1,m) end
v = y sizev = sizey
for i=m:-1:1 % carry out coordinatewise smoothing
    [cs,p{i}] = csaps1(x{i},
        reshape(v,prod(sizev(1:m)),sizev(m+1)), ...
        p{i}, [], w(i))
    [breaks{i},v,l,k] = ppbrk(cs)
    sizev(m+1) = l*k v = reshape(v,sizev)
    if m>1
        v = permute(v,[1,m+1,2:m]) sizev(2:m+1) = sizev([m+1,2:m])
    end
end
output = ppmak(breaks, v)
if length(sizeval)>1, output = fnchg(output,'dz',sizeval) end
if ~isempty(xx)
    output = fnval(output,xx)
else
    [output,p] = csaps1(x,y,p,xx,w)
end
function [output,p] = csaps1(x,y,p,xx,w)
n=length(x) if isempty(w), w = ones(1,n) end
    [xi,yi,sizeval,w,origint,p] = chckxywp(x,y,2,w,p)
```
n = size(xi,1) yd = size(yi,2) dd = ones(1,yd)
dx = diff(xi) divdif = diff(yi)./dx(:,dd)
    if n==2 % the smoothing spline is the straight line interpolant
        pp=ppmak(xi.',[divdif.' yi(1,:).'],yd) p = 
    else
        dxol = dx
        if length(p)>1
            lam = p(2:end) p = p(1)
dxol = dx./lam
        end
        R = spdiags([dxol(2:n-1), 2*(dxol(2:n-1)+dxol(1:n-2)), dxol(1:n-2)],...
            -1:1, n-2,n-2)
        odx=1./dx
        Qt = spdiags([odx(1:n-2), -(odx(2:n-1)+odx(1:n-2)), odx(2:n-1)],...
            0:2, n-2,n)
        W = spdiags(1./w(:,),0,n,n)
        Qtw = Qt*spdiags(1./sqrt(w(:,)),0,n,n)
        if p<0
            QtWQ = Qtw*Qtw p = 1/(1+trace(R)/(6*trace(QtWQ)))
u=((6*(1-p))*QtWQ+p*R)\diff(divdif)
        else
            u=((6*(1-p))*(Qtw*Qtw.')+p*R)\diff(divdif)
        end
    yi = yi - ... (6*(1-p))*W*diff([zeros(1,yd)
diff([zeros(1,yd) u zeros(1,yd])]./dx(:,dd)
zeros(1,yd)])
c3 = [zeros(1,yd) p*u zeros(1,yd)]
c2=diff(yi)./dx(:,dd)-dxol(:,dd).*(2*c3(1:n-1,:)+c3(2:n,:))
    if exist('lam','var')
dx1 = dx.*lam
        pp=ppmak(xi.',...
            reshape([[(diff(c3)./dx1(:,dd)).' ,3*(c3(1:n-1,:)/lam(:,dd)).' , ...
c2.' ,yi(1:n-1,:).' ] , (n-1)*yd,4),yd)
    else
        pp=ppmak(xi.',...
            reshape([[(diff(c3)./dx(:,dd)).' ,3*c3(1:n-1,:)/lam(:,dd)).' ,c2.' ,yi(1:n-1,:).' ] , ...
            (n-1)*yd,4),yd)
    end
    if ~isempty(origint), pp = fnchg(pp,'int',origint) end
    if length(sizeval)>1, pp = fnchg(pp,'dz',sizeval) end
    if isempty(xx)
        output = pp
    else
        output = fnval(pp,xx)
    end
To: The chair, FSTE Research Committee

Subject: Submission of MSc Thesis of Mr. Ramendra Prasad.

I hereby certify that Mr. Ramendra Prasad has completed his Master thesis work on "Ionospheric electron content and L band scintillation study in the South Pacific Region using GPS" up to my satisfaction. The thesis is in a form suitable for examination.

(Dr. Sushil Kumar)
MSc Project Supervisor