**Proceedings of 12th IOE Graduate Conference**
*Peer Reviewed*
**ISSN: 2350-8914 (Online), 2350-8906 (Print)**
**Year: 2022 Month: October Volume: 12**

# GNSS TEC Computation and Comparison using Multi-GNSS Constellations

Saurav Gautam [a], Dinesh Manandhar [b], Krishna Prasad Bhandari [c]

[a, c] *Department of Geomatics Engineering, Pashchimanchal Campus, IOE, Tribhuvan University, Nepal*
[b] *Center for Spatial Information Science (CSIS), The University of Tokyo, Japan*
✉ [a] saurav@ioepas.edu.np, [b] dinesh@csis.u-tokyo.ac.jp, [c] bhandarikrishna@gmail.com

## Abstract

The applications of Global Navigation Satellite System has been rising tremendously, the GNSS system consisting of satellite systems of various nations, which includes Global Positioning System (GPS) by the United States of America, the Global Navigation Satellite System (GLONASS) of Russia, GALILEO of the European Union and BeiDou of China are the systems having global coverage. Regional navigation systems, such as the Indian NavIC and the Japanese QZSS, were also created in addition to GNSS. Calculating the Total Electron Content (TEC), the Ionospheric Scintillations, and Faraday's rotation of electromagnetic waves, one of the main applications of GNSS is to examine the behavior of the ionosphere as a propagation medium. The primary goal of this study is to estimate and evaluate Total Electron Content (TEC) utilizing signals from various GNSS constellations over a receiver at Pashchimanchal Campus in Pokhara, Nepal $(28^{0}15^{'}18.3^{"}N, 83^{0}58^{'}35.1^{"}E)$. For this, a test setup with a multi-frequency GNSS receiver and an estimate of the TEC of the ionosphere using data from July 5, 2022 to August 3, 2022, or GNSS days 186 to 215 of the year 2022, was built. The highest TEC of the range up to (380 TECu) was discovered by examining the data along the GLONASS constellation signal path by R14 satellite. Additionally, the results demonstrated that it is possible to investigate the ionosphere medium using data from a variety of constellations.

## Keywords

GNSS, TEC, Ionospheric Scintillation

## 1. Introduction

### 1.1 Background

The term GNSS refers to a group of satellite constellations that orbit the Earth broadcasting their accurate position and time with the help of highly accurate atomic clocks, to the ground control station networks, and receivers which calculate their ground positions using trilateration. Global Navigation Satellite System now has four globally operating systems which includes Global Positioning System (GPS) by the United States of America, the Global Navigation Satellite System (GLONASS) of Russia, GALILEO of the European Union and BeiDou of China. The Indian Regional Navigation Satellite System (IRNSS) named as NavIC means Navigation by Indian Constellation and Japan's Quasi-Zenith Satellite System (QZSS) are the regional systems. With the seamless operation of the global and regional satellite systems users can be able to access the position, velocity and time (pvt) from more than 100 satellites.[1]

As the satellite signals are available free of cost, tremendous types of research activities along with the civilian applications in the field of positioning, navigation, surveying are possible. With the growing number of applications ionospheric study is also being popular and highly relevant with the availability of GNSS technology. Total Electron Content computation from the different available satellite constellation can provide users with new opportunities and avenues to explore the possibilities of the behavior of the ionospheric scintillations which in high frequency cause disturbances in the radio wave propagation as well as incurs errors of higher value in the positioning provided by the satellite constellation. Therefore, the estimation and removal of the delay caused by the ionospheric phenomenon is important. To remove the error because of the fluctuation in the ionosphere which may be because of daily regular variation due to the earth's rotation or the irregular variation due to the result of Travelling Ionospheric

Disturbances (TID) and ionospheric or geomagnetic storms. Computation and removal of this delay significantly improves the accuracy of and can be performed by using GNSS data, RADAR and ionosonde. [2]

### 1.2 Need of Research

Many studies have been conducted recently in the ionosphere to examine the ionospheric Total Electron Content (TEC) from a network of ground-based regional or global GNSS stations. Ionosphere is one of the biggest sources of error in GNSS-based location, delaying the arrival of the navigation signal. Additionally, due to varied forces from both the top and bottom sides of the ionosphere, the associated inaccuracy continues to fluctuate with respect to time of day, location, and seasons. Single frequency GPS receivers fall short in mitigating these mistakes and rely on alternative methods or model estimations, but dual frequency GPS receivers can reduce the ionospheric error to a higher extent.

There are numerous regional and worldwide ionospheric models available today, including the Global Ionosphere Map (GIM) the Klobuchar model used by GPS and NeQuick model used by Galileo. The experimental datasets and methods are the only ones that can guarantee the dependability of these models. Although these models are available, Survey Grade GNSS receivers can be used to examine a variety of phenomena, including atmospheric scintillation, solar cycles, earthquakes, volcanoes, and lightning [3].

### 1.3 Research Objectives

#### General Objective

The general objective of this study is to estimate the Total Electron Content values of different GNSS constellations.

#### Specific Objective

The specific objective of this study are as follows:

a. Study of algorithms to calculate TEC values form GNSS data.

b. Compare the Total Electron Content values of different GNSS constellation.

### 1.4 Limitations of Study

In this study the raw TEC measurement by the GNSS receiver is used and the proprietary software provided by the receiver's organization is used. The inability to remove the bias affecting TEC is the limitation of this study.

## 2. Literature Review

### 2.1 Ionosphere

Different parts of atmosphere have different characteristics based on their temperature and electron content. However, while dealing with signal propagation to layers are significant which are troposphere and ionosphere [4]. Shown below is a diagrammatic representation of temperature and electron density profile of various layers of atmosphere.

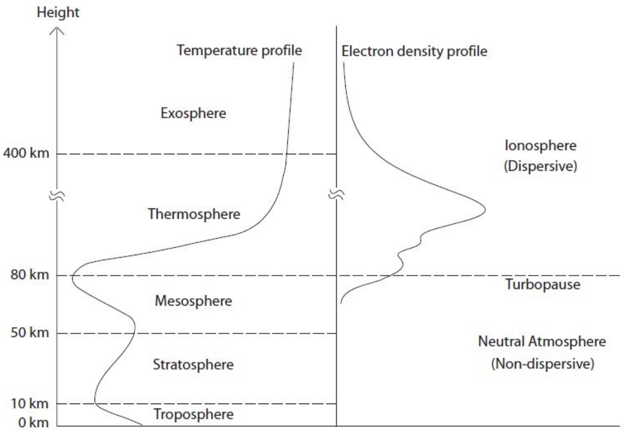

**Figure 1:** Temperature and Electron density profile of various layers of atmosphere [4]

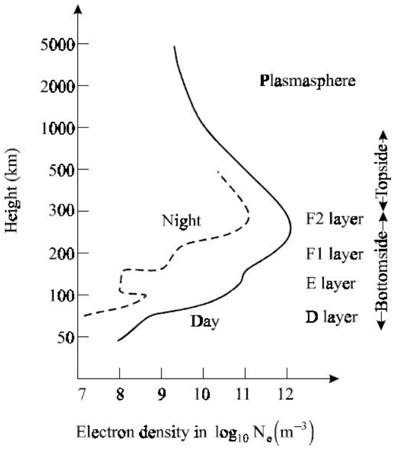

**Figure 2:** Typical vertical profile of ionosphere [6]

The ionosphere which extends from 50 km to 1000 km is the layer of the atmosphere which is ionized by solar radiation. This layer is made up of the D, E, F1, and F2 layers, which are also known as the bottom side of the ionosphere. The topside of the ionosphere is the area between the F2 layer and the upper boundary of the ionosphere. Because of the increased absorption of ultraviolet light and the increase in atmospheric density as altitude decreases, the electron density is greatest in this F2 layer [5].

The D layer is the lowest layer of the ionosphere, located between 50 and 90 kilometers above sea level. Because it only deflects shorter radio waves, this layer has little effect on longer radio waves. By night, electrons are attached to some molecules and atoms, resulting in the formation of negative ions and the possibility of disappearance. However, it reappears in daylight, resulting in the diurnal variation in electron density. The E layer is thin and dense and exists between 90 and 150 kilometers above the ground. Its behavior is determined by solar activity and the angle of the sun at its zenith. This layer does not completely disappear at night, but it is assumed for practical purposes that the electron density of the E layer is zero at night. Due to the E region, which remains charged at night, global radio communication is possible. The F1 layer is located at an altitude of 150 kilometers above the ground. The F layer is divided into two sections: F1 and F2. The F1 layer accounts for 10% of the delay in GNSS signals at the ionosphere layer. Because electron densities are controlled by the zenith angle of the sun, this layer is only visible during the day. The F2 layer is located between 200 km and 1000 km above the ground surface and is critical for GNSS measurements. As a result, this layer is much more unstable in the equatorial region, and the electron density is higher at night than during the day [4].

Different geographic regions of the earth are affected differently by the ionosphere. The equatorial region has the highest peak electron density value. In this region, the amplitude and phase of the signal change frequently. The equatorial region is located between 0 and 20 degrees geomagnetic latitude, resulting in a decrease in electron density at the geomagnetic equator, also known as equatorial anomaly. The daily equatorial anomaly begins in local time between 9:00 and 10:00 and peaks between 14:00 and 15:00. The mid latitude region spans 20 to 60 degrees of geomagnetic latitude. The majority of research and observations have focused on this region because it is home to the majority of countries with ionospheric sensing instruments. This is also the location of our research area. The high latitude region is defined by geomagnetic latitudes ranging from 60 to 70 degrees. Collisional ionization occurs in this region, which is another source of ionization. This is due to the fact that the geomagnetic field lines are nearly vertical in this region, causing charged particles to descend to E layer altitudes (about 100 km).

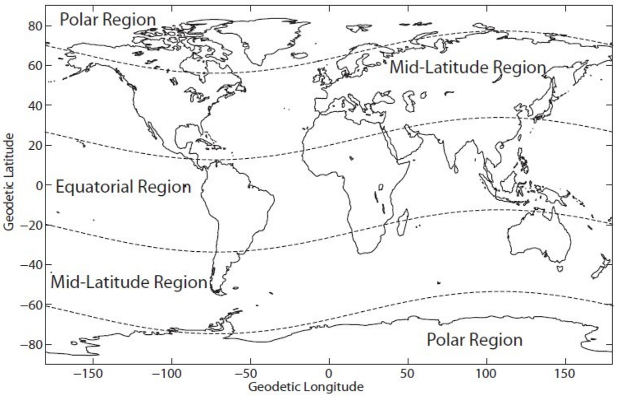

**Figure 3:** Geographic regions of ionosphere according to geodetic latitudes [4]

## 2.2 Ionospheric Scintillation

Ionospheric scintillation, caused by ionospheric irregularities, has two effects on GPS signals, which are broadly classified as refraction and diffraction [7]. These effects are caused by the group delay and the phase advance experienced by the GPS signal as it interacts with the free electrons present in the transmission path. The sun experiences its own seasons, and every 11 years it reaches a time of peak activity known as the solar maximum. As per NOAA's prediction the next solar maximum is anticipated during the middle of 25th Solar Cycle, which occurs between November of 2024 and March of 2026 and is most likely to fall in July of 2025. This is why we need to take into effect the reaction of GNSS signals because of solar activity [8]. Storms in the ionosphere pose an additional risk to GNSS and radio signals by causing disturbances in propagation. Although due to the decades of study of satellite signals has resulted in a clear picture of the ionospheric phenomenon.

## 2.3 TEC

Total electron content is a derived parameter from electron density and is well-defined as the line integral of the density of electrons in the path of transmission.

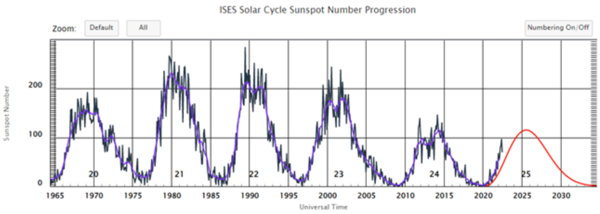

**Figure 4:** Solar cycle 25 prediction, NOAA, July 2022 [8]

$$TEC = \int n_e d\rho$$

The total number of electrons in a cylindrical tube having a cross section of $1m^2$ is represented by TEC. It is measured in TECu, where 1 TECu equals $1016 electrons/m^2$. TEC contains an ionospheric electron distribution projection and can be used to model, reconstruct, and predict ionospheric variability. The widespread use of GPS dual frequency receivers provides a low-cost method of estimating TEC. Short- and long-term variations in the ionosphere and ionospheric disturbances can be analyzed using TEC values. It is determined by the satellite's elevation angle. Because the length of the signal path from the ionosphere varies with satellite position, higher TEC results from lower elevation due to the longer signal path. [5] The following is a visual representation of TEC values:

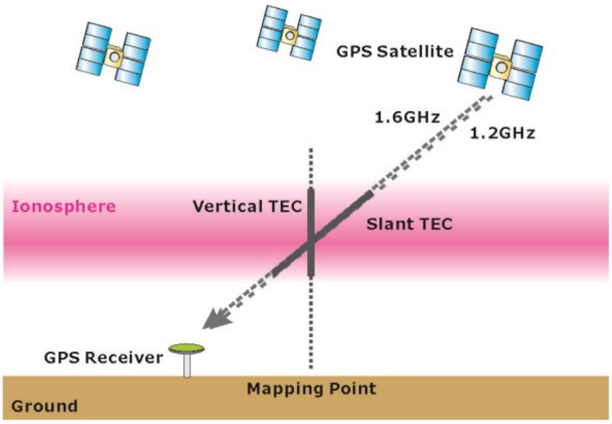

**Figure 5:** Visual representation of TEC values [9]

### 2.3.1 Single Layer Ionospheric approximation

Electron density cannot be directly measured. Mathematical modeling and measurement uncertainties and errors are examples of indirect methods. For the sake of simplicity, the ionosphere is modeled as a single thin layer 400 km above the earth's surface which surrounds the earth at a fixed height and all the free electrons assumed in the ionosphere are said to be concentrated in a single layer.There are various mapping functions available for calculating vertical TEC from slant TEC and vice versa.

### 2.3.2 Ionospheric pierce point

Signal form satellite towards the receiver passes via a point called ionospheric pierce point (IPP) through the ionospheric shell. While the zenith angle at ionospheric pierce point IPP is $z'$ the signal arrives at the receiver having zenith angle z. Here R denotes the average Earth radius, and H denotes the average height of the ionosphere shell.

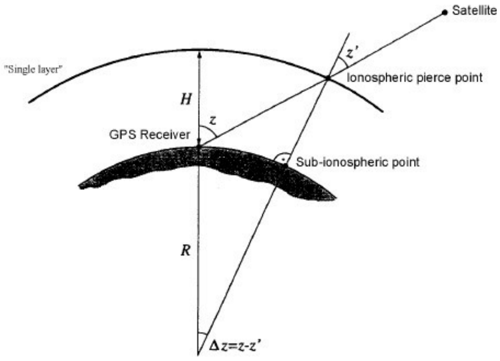

**Figure 6:** Single layer model of the ionosphere[10]

## 3. Research Methodology

Establishment of a multi frequency multi GNSS receiver was performed at, Pashchimanchal Campus, Lamachaur, Pokhara, Nepal, to compute the Total Electron Content (TEC) from the GNSS satellite systems having global coverage. The receiver station, which is mounted on the roof of our institute, is Septentrio PolaRx5e receiver with a multifrequency antenna with high gain . The antenna and receiver are linked by a 25-meter RF cable.

The antenna receives signals from multiple GNSS and regional constellation satellites. However, this study focuses primarily on GNSS constellations to estimate the TEC using real-time observables from July 5th to August 3rd, 2022. The raw data was recorded at a sampling rate of 1Hz in Septentrio Binary Format (SBF). This SBF data was converted into RINEX format using the SBF converter graphical user interface (GUI). The SBF analyzer was then used to calculate parameters such as the number of PRNs, elevation angle, and TEC.

**Figure 7:** GNSS receiver's antenna

**Figure 8:** GNSS receiver data logging and processing setup

As the antenna receives multi GNSS signals form global and regional satellite constellation the data is logged by the receiver at a 1s rate in the form of Septentrio Binary Format (SBF). As this study is used to study the GNSS observables of the period of from July 5th to August 3rd, 2022. Septentrio's proprietary software SBF analyzer was used to analyze the Total Electron Content form different satellite constellation.

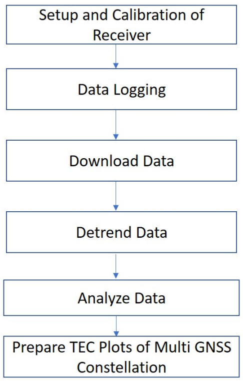

**Figure 9:** Flowchart of Methodology

The value of Total Electron Content (TEC) raw TEC in this case was calculated using the ionospheric differential delay of two carrier phase or code phase observations recorded at two different frequencies (f1 and f2).

$$P^I_{p,k} = D^I_P + c(\Delta t_p(t_e - \Delta t_p(t)) + T^i_p + I^i_{p,k} + M^i_{p,k,g}$$

where,$P^I_{p,k}$ is pseudo-range, $D^p$ is geometric distance between satellite 't' and receiver 'p' , c is speed of light in free space ($3 \times 10^8$ m/s); $\Delta t_p$ is satellite clock error at time of emission ($t_p$) and $\Delta t_p$ Receiver clock error at time of reception. The computation is done for the STEC using the following equations.

$$STEC = \frac{1}{40.3}\left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right)(P_2 - P_1)$$

where, the combinations adopted to calculate the TEC values are GPS TEC(L1-C/A, L2-P(Y)),GLONASS TEC(L1-C/A, L2-C/A), Galileo TEC (L1BC, E6BC), BeiDou TEC (B1I, B2I).

## 4. Analysis and Results

The Total Electron Content values which are estimated using various frequencies of GPS TEC (L1-C/A,L2-P(Y)), GLONASS TEC (L1-C/A,L2-C/A), Galileo TEC (L1BC,E6BC), BeiDou TEC (B1I,B2I) for the period of one month form July 5th 2022 to August 3rd 2022.

TEC values are available for satellites of all constellation and are visualized on which comparative analysis was performed. The computation of GPS TEC fluctuation for all present GPS satellite was done using L1-C/A and L2 P(Y) signals which shows daily variation of GNSS TEC with GNSS time for all available PRNs, the figure shows each PRN with a unique color, a number of PRNs data was utilized to study variation of Total Electron Content over the receivers position

| S.N. | GNSS Constellation | No. of Satellites Tracked | Minimum Value of TEC | Maximum Value of TEC |
|---|---|---|---|---|
| 1 | GPS | 32 | G13 -63.98 | G11 220 |
| 2 | GLONASS | 24 | R03 -263.165 | R13 725.857 |
| 3 | GALILEO | 36 | E05 -68.97 | E02 225.712 |
| 4 | BeiDou | 16 | C08 -97.063 | C07 288.35 |

**Table 1:** Analysis of TEC Values of MultiGNSS Constellation from 1s data

The presented plots of TEC values of each PRN shows crests and troughs of positive and negative values in TEC. All these are resulted due to the (Differential Code Biases) added by satellite as well as the receiver hardware. Like-wise TEC estimated with the data form different global constellations (GLONASS, GALILEO and BeiDou) with their results are shown in the following charts.

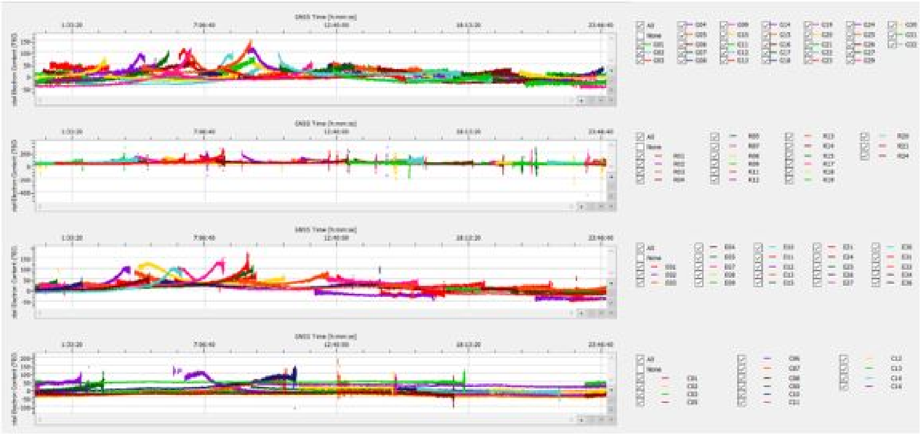

**Figure 10:** TEC Sample Plot of July 3, 2022

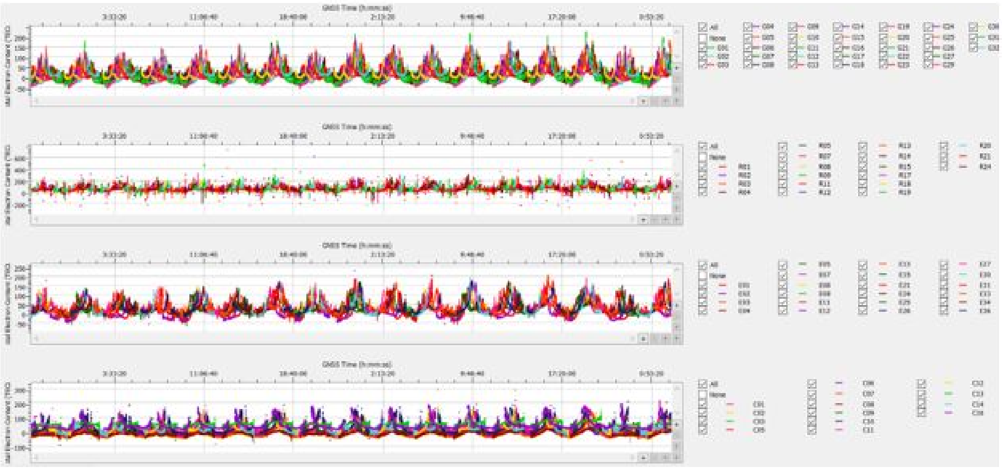

**Figure 11:** TEC Plot of July 3- August 5, 2022

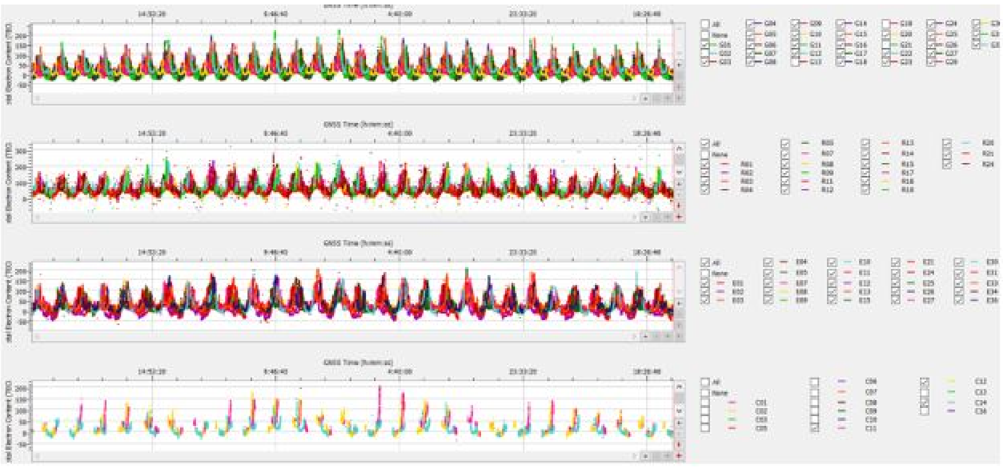

**Figure 12:** 60s detrened TEC Plot of July 3- August 5, 2022 with only MEO BeiDou satellites

In these charts the TEC values are given in the x axis and the time of the day has been shown in the y axis in the topmost plot the GPS TEC has been shown with all PRN of the satellite vehicles while in the second plot form the top GLONASS TEC are demonstrated while in the third plot form the top GALILEO TEC are shown while the bottom plot shows BeiDou TEC of the satellite vehicles which have middle earth orbits.

| S.N. | GNSS Constellation | No. of Satellites Tracked | Minimum Value of TEC | Maximum Value of TEC |
|---|---|---|---|---|
| 1 | GPS | 32 | G13 -62.85 | G11 218.476 |
| 2 | GLONASS | 24 | R21 -232.745 | R14 380.717 |
| 3 | GALILEO | 36 | E05 -68.97 | E13 198.227 |
| 4 | BeiDou | 16 | C12 -38.76 | C16 191.556 |

**Table 2:** Analysis of TEC Values of MultiGNSS Constellation from detrended 60s data

## 5. Conclusion and Recommendations

TThis study presents that use of multi GNSS constellations can be done to observe and study the behaviors of GNSS TEC to study the effects of ionospheric phenomenon's affecting radiowaves propagation as well as delays in GNSS signal which significantly cause problem in high accuracy positioning. Pashchimanchal Campus, Pokhara $(28^{0}15^{'}18.3^{''}N, 83^{0}58^{'}35.1^{''}E)$, Nepal July 5, 2022 to August 3, 2022 i.e day 186 to day 215 of year 2022. The maximum range of TEC value of the range of 380 TECu is measured in GLONASS constellation in the form of spikes. The GPS TEC(L1-C/A,L2-P(Y)),GLONASS TEC(L1-C/A,L2-C/A), Galileo TEC (L1BC,E6BC), BeiDou TEC (B1I,B2I) are a great measure to study the behavior of ionospheric scintillation and hence remove or omit the errors caused due to the high solar activity.

## Acknowledgments

The authors would like to thank Er. Ajay Kumar Thapa and Er. Digvijaya Paudel for their support and motivation in completion of this study.

## References

[1] UNITED NATIONS and OFFICE FOR OUTER SPACE AFFAIRS, *Global Navigation Satellite Systems Education Curriculum UNITED NATIONS*. 2012.

[2] M. A. and M. I. Norsuzila Ya'acob, "GPS Total Electron Content (TEC) Prediction at Ionosphere Layer over the Equatorial Region," Intech, p. 13, 2012, [Online]. https://www.intechopen.com/chapters/9691

[3] L. Osei-poku, L. Tang, and W. Chen, "Evaluating Total Electron Content ( TEC ) Detrending Techniques in Determining Ionospheric Disturbances during Lightning Events in A Low Latitude Region," 2021, doi: 10.3390/rs13234753.

[4] Y. Memarzadeh, *Ionospheric Modeling for Precise GNSS Applications*. 2009.

[5] M. Fedrizzi, E. De Paula, M. Santos, and A. Komjathy, "Mapping the low latitude ionosphere with GPS and the ads in .," no. March 2018, 2002.

[6] A. Komjathy, "Global Ionospheric Total Electron Content Mapping Using the Global Positioning System," Engineering, no. 188, p. 248, 1997, [Online]. Available: http://www2.unb.ca/gge/Pubs/TR188.pdf.

[7] P. M. Kintner, T. Humphreys, and J. Hinks, "GNSS and ionospheric scintillation," Insid. GNSS, vol. 4, no. 4, pp. 22–30, 2009, [Online]. Available: http://www.insidegnss.com/auto/julyaug09-kintner.pdf.

[8] "ESA - Solar cycle 25 prediction, NOAA, July 2022." Available Here (accessed Aug. 30, 2022).

[9] M. Fedrizzi, E. R. De Paula, R. B. Langley, A. Komjathy, I. S. Batista, and I. J. Kantor, "Study of the March 31, 2001 magnetic storm effects on the ionosphere using GPS data," Adv. Sp. Res., vol. 36, no. 3, pp. 534–545, 2005, doi: 10.1016/j.asr.2005.07.019.

[10] P. Wielgosz, D. Grejner-Brzezinska, and I. Kashani, "Regional Ionosphere Mapping with Kriging and Multiquadric Methods," J. Glob. Position. Syst., vol. 2, no. 1, pp. 48–55, 2003, doi: 10.5081/jgps.2.1.48.