GPS SATELLITE BASED DATA ANALYSIS OF TOTAL ELECTRON CONTENT OF THE IONOSPHERE FOR INDORE CITY

REPORT

BY

ROHAN PATTNAIK
B.TECH, CSE
IIIT, BHUBANESWAR

AND

MRADUMAY SADH
INT. M.SC., PHYSICS
SVNIT, SURAT

UNDER THE GUIDANCE OF
PROF. DR. ABHIRUP DATTA

Submitted to the Center of Astronomy
Indian Institute of Technology
Indore, India
May-July 2016

[July 4, 2016 at 4:14 – Last Updated]

Rohan Pattnaik and Mradumay Sadh: *GPS satellite based data analysis of Total Electron Content of the Ionosphere for Indore City*, Report

Submitted to the Center of Astronomy IIT Indore as report of the Summer Internship Project carried out during May-July, 2016

SOURCE CODE:
https://github.com/rohanp11/IITIGNSSR

LOCATION:
Indore, India

TIME FRAME:
May-July 2016

ACKNOWLEDGEMENTS

The authors would like to sincerely thank the project guide, Dr. Abhirup Datta who has been a really patient and precise adviser. Also we would like to thank the Head of Department for the Center of Astronomy, Dr. Siddarth Mallu, who has been there every time we were in need of his guidance. The kind of nurturing atmosphere that we experienced here at IIT Indore is what fuelled our enthusiasm to keep working. We are also grateful to all the people who have contributed to this project through their research and knowledge.

ABSTRACT

The aim of our project is to extract valuable subset of data from the data received from the GNSS satellites by the PoLaR-xS GNSS dual-frequency receiver located at IIT Indore, Simrol Campus, and use it to analyse the TEC(Total electron content) in the Ionosphere. We have plotted the Total electron content with time and noticed the diurnal trend and other quintessential elements which can be analysed with the TEC data in the equatorial anomaly crest, namely Indore.

CONTENTS

LIST OF FIGURES

ACRONYMS

TEC Total Electron Content

STEC Slant Total Electron Content

VTEC Vertical-Total Electron Content

Iono Ionospheric

GNSS Global Network Satellite System

ISMR Ionospheric Scintillation Monitoring Records

ASCII American Standard Code for Information Interchange

SBF Septentrio binary format

PRN Pseudo Random Noise

SVID Satellite-Vehicle Identification number

GPS Global Positioning System

GLONASS Global Navigation Satellite System

TOW Time of Week

[July 4, 2016 at 4:14 – Last Updated]

1

INTRODUCTION

1.1 WHAT IS THE IONOSPHERE?

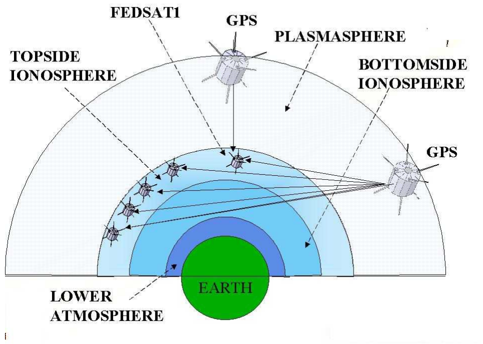


Figure 1: Location of Ionosphere and GPS satellites

The ionosphere is defined as the layer of the Earth's atmosphere that is ionized by solar and cosmic radiation. It lies 75-1000 km (46-621 miles) above the Earth. (The Earth's radius is 6370 km, so the thickness of the ionosphere is quite tiny compared with the size of Earth.) Because of the high energy from the Sun and from cosmic rays, the atoms in this area have been stripped of one or more of their electrons, or "ionized," and are therefore positively charged. The ionized electrons behave as free particles. The Sun's upper atmosphere, the corona, is very hot and produces a constant stream of plasma and UV and X-rays that flow out from the Sun and affect, or ionize, the Earth's ionosphere. Only half the Earth's ionosphere is being ionized by the Sun at any time.[3]

1.2 IMPORTANCE OF THE STUDY OF IONOSPHERE

The signals coming from GPS satellites are hugely deviated from their original position because of interference due to the electrons present in the ionosphere. To minimise this or eradicate this error it is imperative to understand the total electron count in the Ionosphere.

1.3 TOTAL ELECTRON CONTENT

The signals coming from GPS satellites are hugely deviated from their original position because of interference due to the electrons present in the ionosphere. To minimise this or eradicate this error it is imperative to understand the total electron count in the Ionosphere.
The total electron count is the integration of the electron density along the total path between the receiver and the Satellite. So, basically it is the column number density.According to [1]

$$\mathrm{TEC} = \int n_e(s)ds$$

Where, the number density is path dependent and depends on the path from receiver to satellite, And ds is the infinitesimal element for which the number density is independent of path. The TEC value is obtained from the satellite data in an interval of 15 seconds. From interval T-45 seconds to T=0 seconds. We have fetched the readings of the TEC, at T=0. The TEC values in the plot have an interval of one minute.

1.4 OTHER BASIC DEFINITIONS

- **VTEC:** The vertical TEC is the electron count in which the electron number density is integrated along the path perpendicular to the surface of the earth.[1] It is calculated by multiplying sine of the elevation of the satellite with the total electron count.[2]
- **Iono Delay:** The Ionospheric delay is calculated by the following formula,according to[1]

  $$D = \frac{\mathrm{TEC} * 40.3}{frequency^2}$$

  The delay is calculated in metres and it tells us, how much the signal has deviated.

2 THE GNSS RECIEVER AND OVERVIEW OF THE PROGRAM

2.1 POLAR-XS GNSS RECEIVER

Figure 2: The antenna and device comprising the Polar-xS GNSS Receiver at IIT-Indore

The PolaRxS is a multi-frequency multi-constellation receiver dedicated to ionospheric monitoring and space weather applications. The PolaRxS incorporates a state-of-the-art triple-frequency receiver engine and an ultra low noise OXCO frequency reference in a rugged housing. The housing provides a multitude of interfaces including USB and Ethernet. An intuitive User Graphical Interface is provided for data logging and remote control. Specifically for space weather and ionosphere monitoring applications, the logging tool (RxLogger) supports continuous TEC and scintillation indices logging and monitoring.

2.1.1 *Important points about the receiver*

- We have a dual frequency receiver which operates on L-1 and L-2 bands.
- The signals coming from the satellites are right circularly polarised which is received by the receiver and converted into ASCII format and saved in that format as an SBF file, which is then converted to a comma delimited ISMR file by the sbf2ismr program.
- Each day a new folder is generated for that particular day and 24 .ismr files are created each hour from the data collected for each folder.

- As a consequence of this conversion the ISMR files are smaller in size than the SBF files.

2.1.2 *Location of Indore and its Importance*

Latitude of Indore: 22.7196
Longitude of Indore: 75.8577

The latitude of Indore suggests that it is the equatorial anomaly crest region. Therefore, Location of Indore is important for the study Ionosphere, since it has a increased ionization and hence increased Total Electron content.

2.2 IMPORTANT INFORMATION REGARDING THE PROGRAM

```
Col  1: WN, GPS Week Number
Col  2: TOW, GPS Time of Week (seconds)
Col  3: SVID
Col 23: TEC at TOW (TECU), taking calibration into account (see -C option)
```

Figure 3: Columns of the .ismr file and description of the data in them

We have extracted the TEC data from column 23, that is, at TOW. The time column is the GPS time of week TOW column 2,which is later converted to local time.
We have plotted data for various satellites, distinguished in the graph

1 - 37	: PRN number of a GPS satellite
38 - 61	: Slot number of a GLONASS satellite, with an offset of 37
71 - 102	: PRN number of a GALILEO satellite, with an offset of 70
120 - 140	: PRN number of an SBAS satellite
141 - 172	: PRN number of a COMPASS/BEIDOU satellite, with an offset of 140
181 - 187	: PRN number of a QZSS satellite, with an offset of 180

The value "62" is used for GLONASS satellites of which the slot number is not known.

Figure 4: Part of the documentation describing the SVID column

with different colours. Each satellite is identified with a unique PRN "pseudo-random noise" number or SVID (Satellite-Vehicle Identification number) code.

2.3 PROGRAM HIGHLIGHTS

- The program is completely developed in Python. It uses the pandas, numpy and matplotlib libraries of Python for data handling and plotting.
- The program displays the range of dates for which data is available.
- The program takes dates as input and asks to choose between GPS and GLONASS satellite constellations for which the plot is required.
- The files and folders are named according to the year and the day of the year. Thus the program first converts the user entered date into the file name format for that day and fetches the corresponding file from the folder.
- The program extracts then data from the time and TEC columns and groups them by the PRN number of the satellite present in column 3.
- Then it converts them into two individual numpy arrays, one containing the TEC data and other containing time stamps, the time is converted into local time and the curve is plotted.
- The Program has the following 3 options for generating the plot according to user's choice:
  1. TEC vs Time
  2. Vertical TEC vs Time
  3. Iono-delay vs Time
- The combined plot has data from various Satellites (distinguished by their colours) which belong to a unique constellation. The plot shows the variation in either TEC, VTEC, iono-delay values as per each satellite for any number of days.

2.4 REASONS FOR NOT CHOOSING GLONASS SATELLITE CONSTELLATION

The variation in GLONASS satellites is because the sbf2ismr program doesn't correct for the satellite induced biases, hence it is not ideal for analysis.

Satellite system	TEC signal combination	Default handling of satellite-induced biases
GPS(1)	L1P-L2P	The correction (T_{GD}) transmitted by GPS satellites is applied.
GLO	L1CA–L2CA	Uncorrected
GAL	E1–E5a	The correction (BGD(E1,E5a)) transmitted by Galileo satellites is applied.
BDS	B1–B2	The correction (T_{GD1},T_{GD2}) transmitted by BeiDou satellites is applied.
QZSS	L1CA-L2C	The correction (T_{GD}) transmitted by QZSS satellites is applied.
SBAS	L1CA-L5	Uncorrected

) For GPS, the TEC is based on the P-code measurements (as opposed to the C/A-code) on L1 and L2. Therefore, there is no need for correction of the L1P-L1CA satellite biases.

Figure 5: Snapshot from Polar-xS documentation showing no correction for GLONASS satellite constellation

3 RESULTS AND ANALYSIS

3.1 ANALYSIS OF TOTAL ELECTRON CONTENT

3.1.1 *The variation of Total Electron Content with Time*

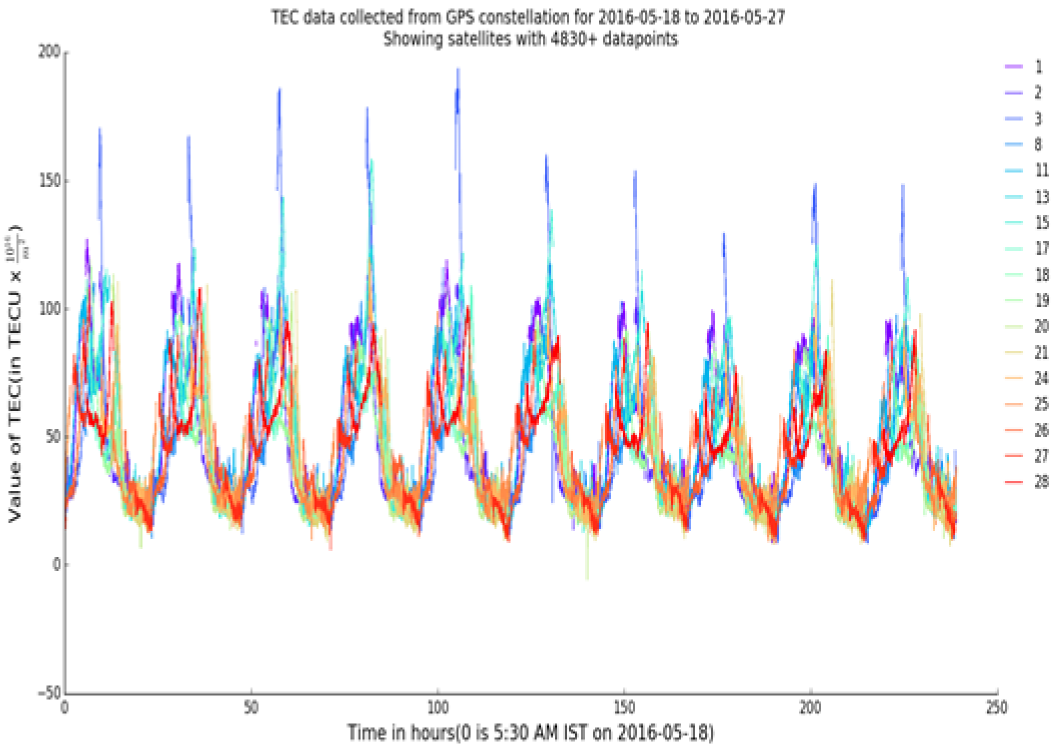


Figure 6: A 10 day plot from 18th May 2016 to 27th May 2016

The diurnal trend is clearly visible in the above graph, where the peak occurs in the afternoon at around 2 to 3 PM IST because radiation from the Sun is maximum during this period of the day which results maximum ionization.

3.1.2 *The variation of Total Electron Content with Elevation of the satellite*

The elevation of the satellites varies with time and with elevation TEC also varies. Theoretically, the variation should have a negative slope, that is, the TEC should decrease with increasing elevation and vice versa.
However, the plots show a deviation from theoretical predictions.

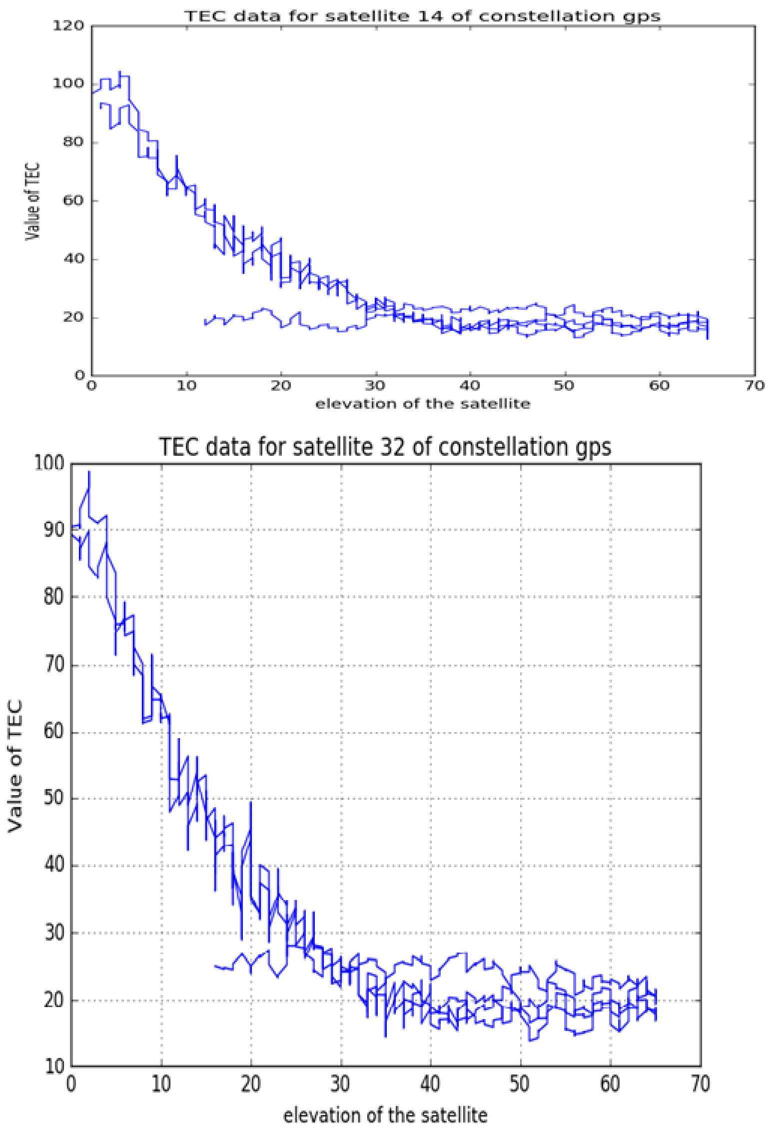


Figure 7: TEC vs Elevation of satellite plotted for two consecutive days

Irregular Plots:

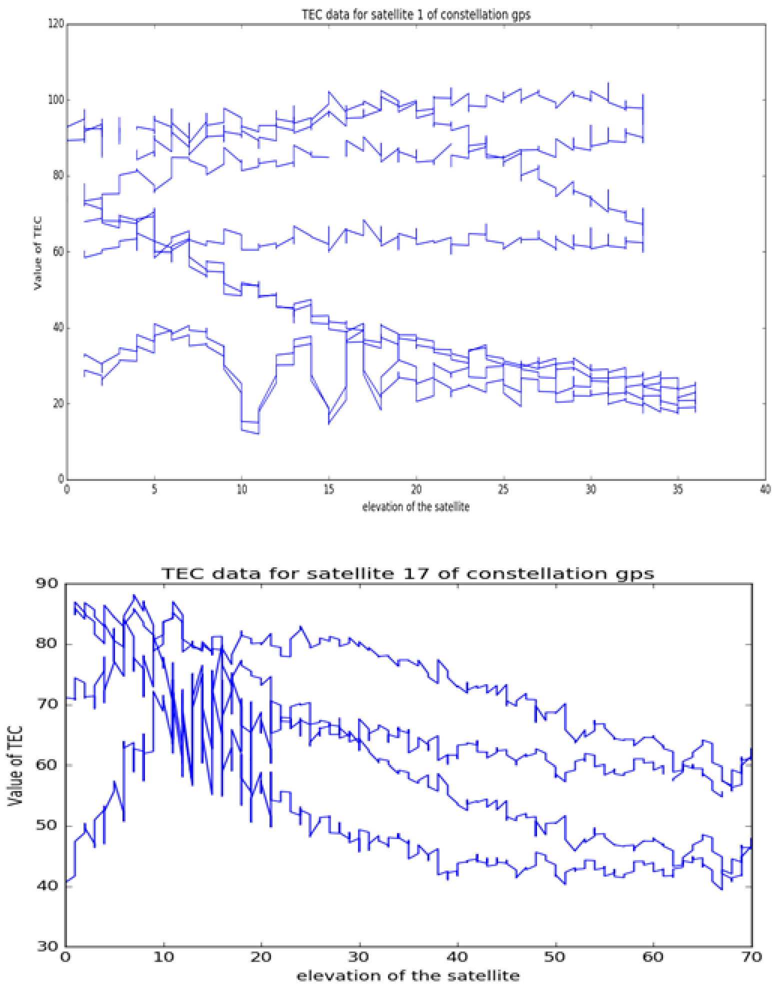


Figure 8: TEC vs Elevation of satellite plotted for two consecutive days that show erratic nature of the variation

3.2 ANALYSIS OF THE TEC DATA FOR CONVERSION INTO VTEC FROM STEC

The TEC data which is coming from satellites is called Slant TEC (STEC) and it depends on the elevation of the satellite, since it varies with the elevation, different satellites at different elevation give different TEC which makes the diurnal trend of TEC disperse. Therefore, we need to convert it into vertical TEC or VTEC.

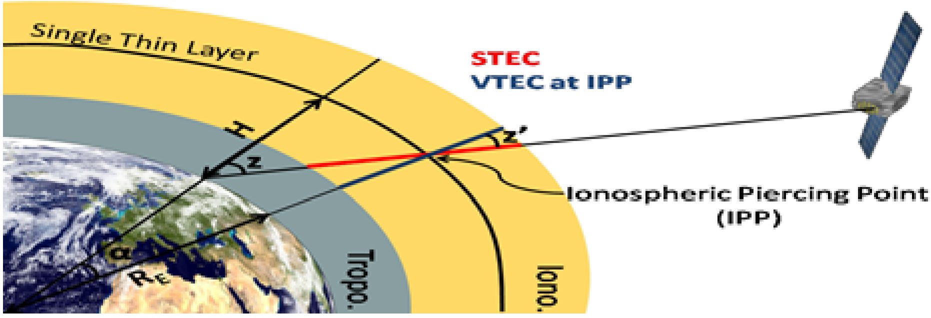


Figure 9: Conversion of STEC to VTEC

The Klobuchar Ionospheric model is brought into consideration for the conversion, that is, we assume the ionosphere as a layer 350 km above the surface of the earth. Now, Vertical TEC is calculated by the following function,

$$\mathrm{VTEC} = \frac{(\mathrm{STEC} - [bR + bS])}{S(E)}$$

[2]

$$S(E) = \frac{1}{(\cos\chi')}$$

]

R_x =mean radius of earth,6731 km, h_m = altitude of the IPP, χ =elevation angle, and $\chi' = (90^o - \chi)$
The sbf2ismr program calibrates the STEC values, so biases are thereby corrected .Now, since we have assumed the height of the ionosphere(altitude of IPP) at 350 km, it can be neglected while addition to radius of the earth, therefore the net formula for conversion boils down to,

$$VTEC = STEC * \sin(elevationangle)$$

The Klobuchar model is not entirely accurate in modelling the ionosphere, therefore the domain of validity of this relation matches inadvertently with that of the Klobuchar model.
The STEC values decrease with increasing elevation because of the spatial anisotropy of the ionosphere. However with VTEC, the elevation factor should be eliminated.

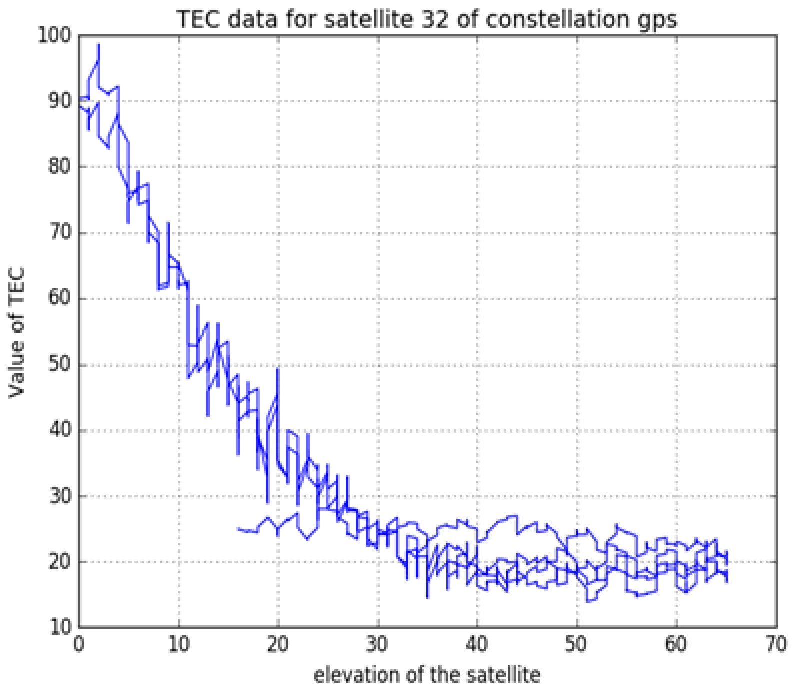


Figure 10: Variation of STEC with elevation for satellite SVID 32 of the GPS constellation

The above graph tells us how STEC decreases with increasing elevation of the satellite. The main objective of converting to VTEC is to remove this dependency.

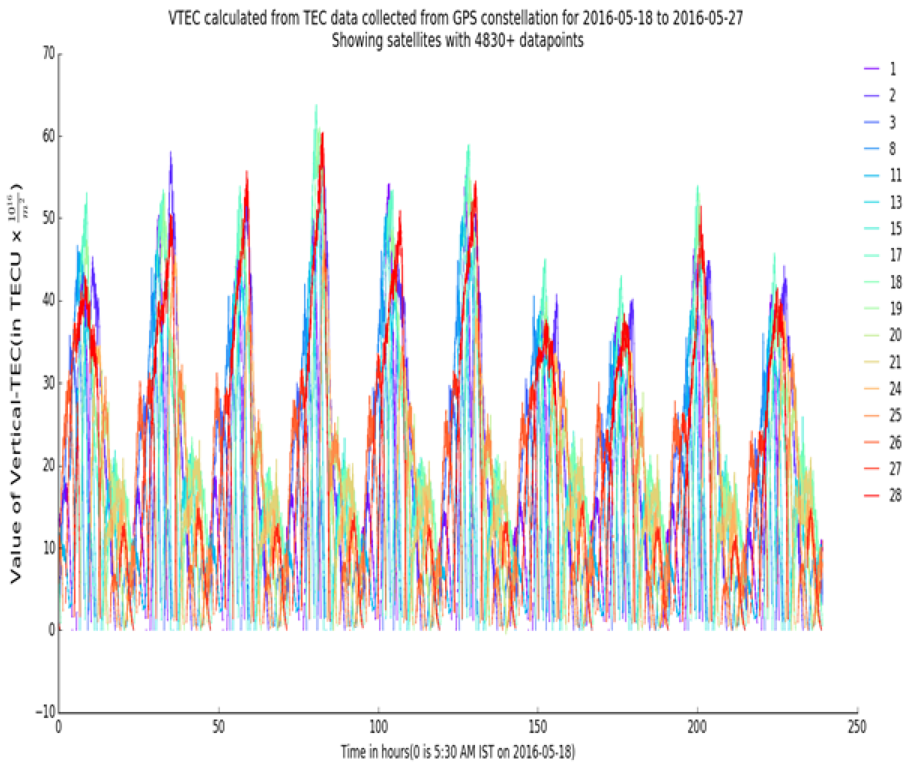
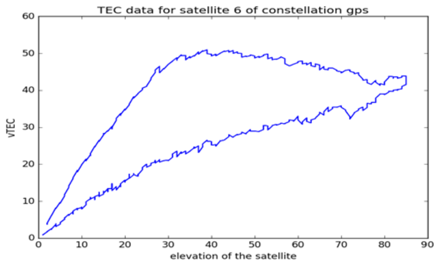


Figure 11: Variation of VTEC with time for satellites of the GPS constellation for 10 days

However, the curve obtained above is inappropriate because it still shows different values for each satellite, the peaks for different satellites vary by as much as 30TECU, whereas theory suggests that the values should be same for all.



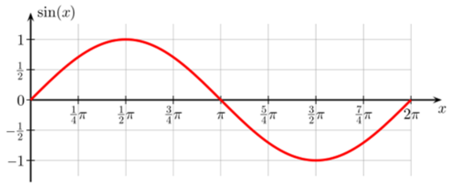
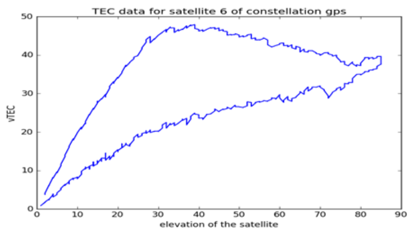


Figure 12: Variation of VTEC with elevation for $VTEC = STEC * \sin(elevationangle)$

The variation of VTEC vs. elevation instead of being a flat line takes the above form, which suggests that VTEC still depends on elevation. The reason we deduced for this variation of VTEC with elevation is that, sine is overcompensating the lower values of TEC and under compensating the higher values of TEC. Therefore we chose a curve which is less steep than sine, that is, hyperbolic tangent.However, the variation still persists and the following curve depicts that,



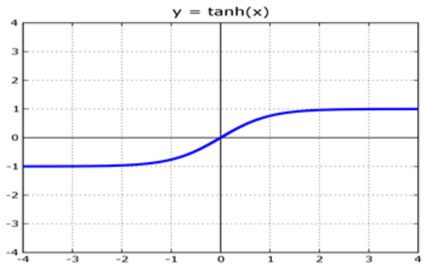


Figure 13: Variation of VTEC with elevation for $VTEC = STEC * \tanh(elevationangle)$

To make the curve less steeper we used another function, which we deduced,

$$VTEC = STEC * \left(\frac{elevation^{0.25}}{\sqrt{90 - elevation}} \right)$$

which almost made the VTEC vs. time curve flat but for higher values of elevation it overcompensated the values.

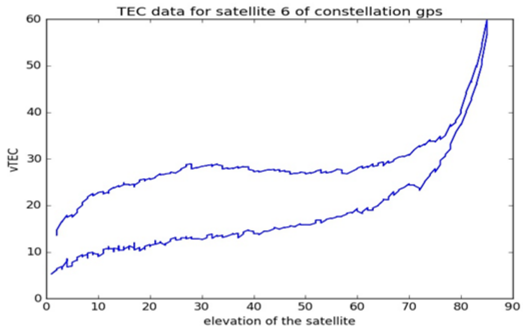


Figure 14: Variation of VTEC with elevation for $VTEC = STEC * \left(\frac{elevation^{0.25}}{\sqrt{90 - elevation}}\right)$

Also, this function did not make VTEC constant for every satellite, for some satellites the variation still persisted,

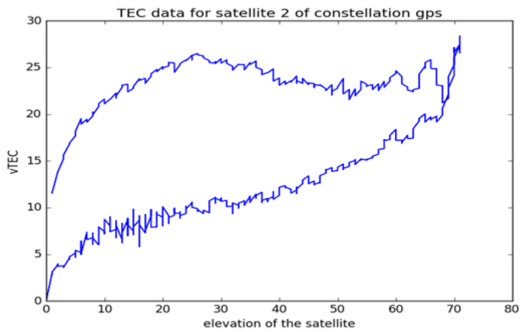


Figure 15: Variation of VTEC with elevation for $VTEC = STEC * \left(\frac{elevation^{0.25}}{\sqrt{90 - elevation}}\right)$ of satellite SVID 2

Since there is an ambiguity in the variations of different satellites, modelling the STEC to VTEC function becomes extremely intricate with brute force method.

Another thing which could be done was to plot the curve for those satellites whose TEC value is not varying erratically with elevation, so we plotted the curve for 3 satellites, namely PRN-17, 19, 28.

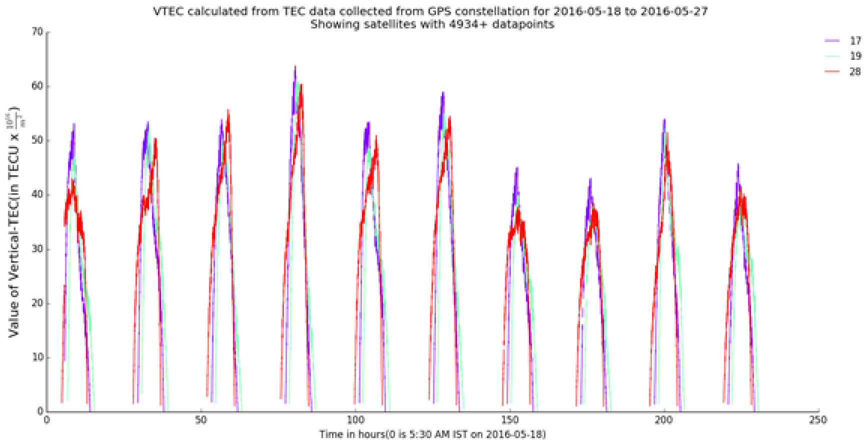


Figure 16: Variation of VTEC with elevation for VTEC of 3 satellites

The variation or difference has reduced to 4-8 TECU between the respective peaks of the VTEC, which was earlier approaching 20-30TECU when all satellites were considered. A zoomed out picture showing reduced variations,

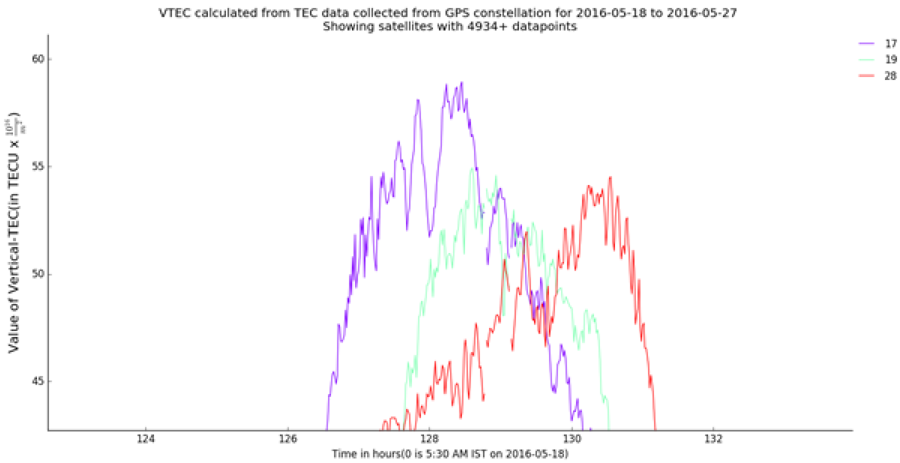


Figure 17: Zoomed picture of Variation of VTEC with elevation for VTEC of 3 satellites

It is evident from above, graph that the variations have reduced to 3-4 TECU from 20-25 TECU which was the case when all satellites were considered.

3.3 ANALYSIS OF IONO-DELAY VS TIME

The graph obtained from the program by converting TEC into Iono-delay and plotting it against time is given below. It shows the same characteristics as that of the TEC vs time curve.

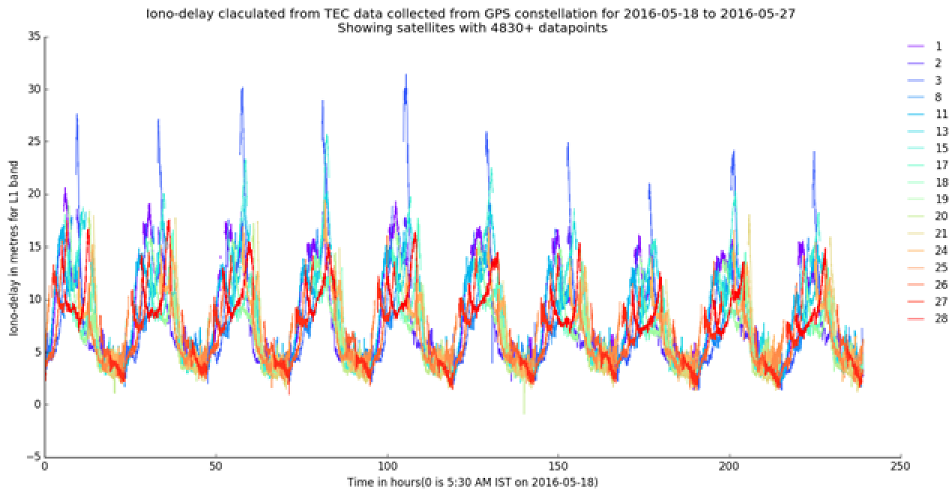


Figure 18: Variation of Iono-delay vs Time for 10 days

3.4 GEOMAGNETIC STORMS AND THEIR EFFECTS

The geomagnetic storms are disturbances produced in the earth's magnetosphere produced because of solar winds. The extent of geomagnetic storms are determined by the planetary K-index (Kp index).When Kp index exceeds or is equal to 5 then it's a geomagnetic storm. The storm results in a substantial increase in the TEC values which can be depicted from the following graph, the days when geomagnetic storms occurred on 21st, 28th may and 5th June. The graph is between VTEC and time,

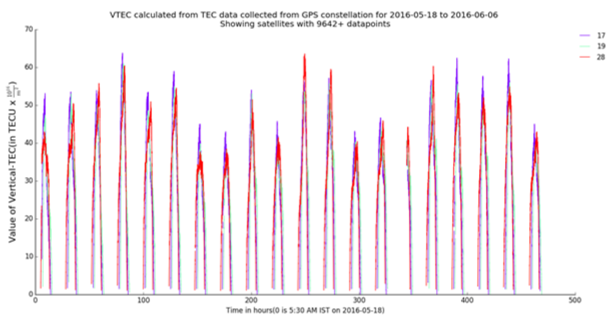
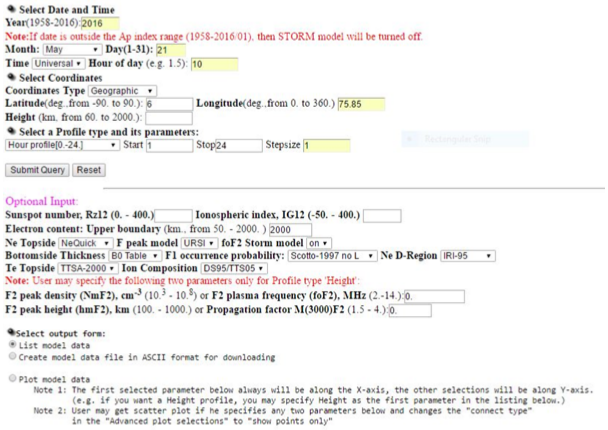


Figure 19: Variation of V-TEC vs Time for 20 days

3.5 EQUATORIAL ANOMALY

The equatorial anomaly is formation of a crest in ionization at ±17® from the geomagnetic equator and formation of a trough at the geomagnetic equator. Indore happens to be at the equatorial anomaly crest, therefore we have a substantial increase in TEC in Indore, and it can be tested by checking the values at the geomagnetic equator. For checking the values at the geomagnetic equator, we used the International reference ionosphere model (IRI). The graph of VTEC depicting values at equatorial crest and trough is shown below, and we can clearly see a difference of 27 TECU in the peak values. The geographic latitude for is geomagnetic equator is taken as 6 degrees.


Select Date and Time
Year(1958-2016): 2016
Note: If date is outside the Ap index range (1958-2016/01), then STORM model will be turned off.
Month: May Day(1-31): 21
Time Universal Hour of day (e.g. 1.5): 10
Select Coordinates
Coordinates Type Geographic
Latitude(deg.,from -90. to 90.): 6 Longitude(deg.,from 0. to 360.) 75.85
Height (km, from 60. to 2000.):
Select a Profile type and its parameters:
Hour profile[0.-24.] Start 1 Stop 24 Stepsize 1
Submit Query Reset

Optional Input:
Sunspot number, Rz12 (0. - 400.) Ionospheric index, IG12 (-50. - 400.)
Electron content: Upper boundary (km., from 50. - 2000.) 2000
Ne Topside NeQuick F peak model URSI foF2 Storm model on
Bottomside Thickness B0 Table F1 occurrence probability: Scotto-1997 no L Ne D-Region IRI-95
Te Topside TTSA-2000 Ion Composition DS95/TTS05
Note: User may specify the following two parameters only for Profile type 'Height':
F2 peak density (NmF2), cm^{-3} ($10.^3$ - $10.^8$) or F2 plasma frequency (foF2), MHz (2.-14.): 0.
F2 peak height (hmF2), km (100. - 1000.) or Propagation factor M(3000)F2 (1.5 - 4.): 0.

Select output form:
List model data
Create model data file in ASCII format for downloading

Plot model data
Note 1: The first selected parameter below always will be along the X-axis, the other selections will be along Y-axis.
(e.g. if you want a Height profile, you may specify Height as the first parameter in the listing below.)
Note 2: User may get scatter plot if he specifies any two parameters below and changes the "connect type"
in the "Advanced plot selections" to "show points only"

Figure 20: Snapshot of the webpage of IRI

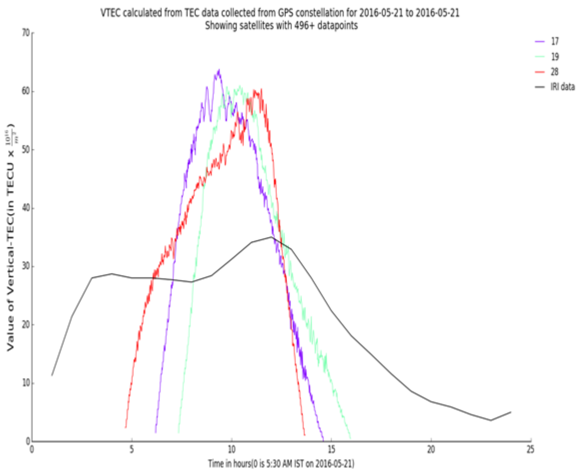


Figure 21: Plot of VTEC vs Time along with IRI data

The black curve represents the IRI data which lies clearly below the data from Indore.

4 CONCLUSION

Our program gives the TEC, VTEC and Ionospheric delay plots according to the choice of the user for any day after 17th may, for study and analysis. It can produce plots for a single day and also for multiple days. The GPS satellites are the most reliable source of TEC information and plots because the satellite biases are corrected for them. We found VTEC values are more reliable because the elevation of the satellite doesn't become a problem, for analysing the electron content values. Also, the Iono-delay plots tell us that signal deviates as high as 30 metres during the afternoon, which is a subject of concern. The location of Indore happens to be at the Equatorial anomaly crest region, therefore we have an appreciable increase in TEC values in Indore, which has been depicted in the report, also the increment in VTEC during the day on which Geomagnetic storms occured, has been depicted.
The study of Total electron content of ionosphere is important for improving GPS navigation and our program provides the initial steps for the analysis of the same.