Evaluation of long term solar activity effects on GPS derived TEC

Azad A Mansoori, Parvaiz A Khan, Rafi Ahmad, Roshni Atulkar, Aslam A M, Shivangi Bhardwaj, Bhupendra Malvi, P K Purohit and A K Gwal

1Space Science Laboratory, Department of Physics & Electronics, Barkatullah University, Bhopal – 462026, MP, India
2Department of Electronics and Communication Engineering, Islamic University of Science and Technology, Pulwama-192122, J & K, India
3National Institute of Technical Teachers’ Training and Research, Bhopal – 462002, MP, India

Email: azadahmad199@gmail.com

Abstract. The solar activity hence the solar radiance follows a long term periodic variability with eleven years periodicity, known as solar cycle. In the present problem we investigate the long term behaviour of the ionosphere with the eleven year cyclic solar activity. Under the present study we characterize the ionospheric variability by Total Electron Content (TEC) using measurements made by Global Positioning System (GPS) and solar cycle variability by various solar activity indices. We make use of five solar activity indices viz. sunspot number (Rz), solar radio Flux (F10.7 cm), EUV Flux (26-34 nm), flare index and CME occurrences. The long term variability of these solar activity indices were then compared and correlated with the variability of ionospheric TEC, at a mid latitude station, Usuda (36.13N, 138.36E), of Japan, during the solar cycle 23 and ascending phase of cycle 24. From our study, we found that long term changes in the ionospheric TEC vary synchronously with corresponding changes in the solar activity indices. The correlation analysis shows that all the solar activity indices exhibit a very strong correlation with TEC (R =0.76 –0.99). Moreover the correlation between the two is stronger in the descending phase of the solar cycle. The correlation is found to be remarkably strongest during the deep minimum of the solar cycle 24 i.e. between 2007- 2009. Also we noticed a hysteresis effect exists with solar radio flux (F10.7 cm) and solar EUV flux (26-34 nm). This effect is absent with other parameters.

1. Introduction
The solar activity is characterised with a variation pattern of eleven years called solar cycle. During which there occurs periodic variation in the emission of radiation from the Sun. It has been now established that the primary source for the formation of the Earth’s ionosphere are the solar extreme ultraviolet radiations (EUV) and solar X-rays [1]. The solar EUV and X-ray radiation can vary by more than a factor of 2 from solar minimum to solar maximum and by as much as 50% during a solar rotation i.e. these solar radiations follow the solar cycle variation [2, 3, 4, 5]. Therefore the regular or solar cycle variations in solar EUV and X-ray radiations will affect the variability and dynamics of the Earth’s ionosphere. Since the variation of solar X-ray and extreme ultraviolet (EUV) radiations are the main cause for changes in the ionosphere, in the absence of continuous long term records of these fluxes, solar proxies have been used to represent solar emissions. Sunspot number (Rz), solar 10.7 cm
radio flux (F10.7) are the generally used as solar proxies [6]. Ionosphere is highly variable in space and time (diurnal, seasonal and solar cycle), with geographical location (low-latitudes, equatorial regions, high-latitudes and mid-latitudes), and with solar and geomagnetic disturbances [7, 8, 9]. Several studies have revealed the solar cycle effects of ionosphere [10, 11, 12] In the studies conducted in past, the solar cycle effects on the ionosphere have been realized by using different ionospheric parameters derived from ground based and satellite based measurements, such as Total Electron Content (TEC), critical frequency (foF2), peak electron density (NmF2) and peak height (hmF2) of the F2 layer [1, 3, 4, 6, 13, 14, 15, 16, 17, 18, 19, 20, 21], as well as various solar activity indices like sunspot number, solar 10.7 cm radio flux, EUV Flux etc. These studies have revealed several interesting and important features of the solar cycle variation of ionospheric parameters. These studies revealed that ionosphere parameters such as critical frequency (foF2), the peak electron density (NmF2) and the Total Electron Content (TEC) are strongly controlled by solar activity in a rather complicated manner. It is found that the relationship of the ionospheric parameters : TEC, foF2, NmF2 and hmF2 with Sunspot Number, F 10.7 cm, EUV flux and X-ray flux may be roughly linear [16, 22], two segmented linear pattern [11], quadratic or higher order polynomial[17, 23]. Recent works show the ionospheric parameters approximately increase linearly with solar proxies during low and medium solar activity levels; however they tend to saturate during high solar activity level [13, 14, 16, 20, 21, 24, 25]. The true manifestation of this saturation effect is still not fully understood. In some studies a hysteresis effect has also been reported which is small at low and high latitudes but substantial at mid latitudes [3, 22]. Ionospheric research gets a significant attraction from the GPS community because ionosphere has practical importance in GPS applications as it influences the trans-ionospheric radio wave propagation. The ionospheric parameter which produces most of the effects on radio signals is Total Electron Content (TEC). By modelling TEC, the evaluation of the ionospheric error and corrections of these errors can be done for differential GPS. GPS signals experiences time delay when passing through the ionosphere. This delay of signals is directly proportional to integrated free electron density (TEC) along the ray path from the GPS satellite to a receiver. The magnitude of TEC is highly variable in space and time and it is a function of geomagnetic latitude, local time, season and 11 year sunspot cycle [26, 27, 28, 29]. The starting of the cycle 24 or the ending of cycle 23 was quite unique. During this period solar activity remained remarkably low. The sun went spotless for more than 70% of the days of the years 2007-2008. This represents the deep minimum of the cycle 24. It has been found that during this deep minimum the relationship of ionospheric parameters with solar indices like F10.7, deviated considerably from the past behaviour [30] as well as IRI over estimated the values for this period [31]. Therefore this period is interesting to study the behaviour of ionosphere under such a low solar activity.

2. Data Sets and Methodology
To investigate the long term variability of the ionospheric TEC with solar cycle variability we have considered the solar cycle 23 and initial phase of solar cycle 24 i.e. 1998 – 2011 as our period of study. For the purpose a mid latitude station of Japan namely Usuda (36.13N, 138.36E) is been selected. To characterize the long term solar activity we have taken five solar activity indices viz Sunspot Number (Rz), solar radio Flux (F 10.7 cm), EUV Flux (26-34 nm), Flare Index and CME Occurrences. The data for Sunspot Number, Solar radio flux and Flare Index were taken from National Geophysical Data Center (NGDC) URL: http://www.ngdc.noaa.gov/. The CME occurrences were calculated from the CME catalog provided at SOHO URL: http://cdaw.gsfc.nasa.gov/CME_list/. The EUV flux (26-34nm) was taken from the URL: http://www.usc.edu/dept/space_science/sem_data/sem_data.html. Then we constructed the long term averages of these data sets and prepared the monthly and yearly averaged values of these data and then investigated their relationship with ionospheric TEC. A network of GPS receivers is spread almost over the entire globe to accomplish the regular monitoring of the ionosphere. A huge database of the data collected at the International GPS Service
(IGS) stations is being maintained. The data is free to users. For our study, we have selected a mid latitude station of Japan, Usuda (36.13N, 138.36E). The TEC data were taken from the URL: http://sopac.ucsd.edu/dataArchive/. The raw data taken is in RINEX format, which is then processed to get the required Total Electron Content (TEC). The temporal resolution of the data is usually 30s. We then prepared the monthly and annual mean values of all the solar indices and the ionospheric parameter TEC to investigate the long term variability of TEC with selected solar indices that characterize long term cyclic variability of solar activity.

3. Results and Discussion
Primarily we compare the monthly changes of each five selected solar indices with the corresponding changes in the TEC. Figure 1 shows the changes in monthly averaged values of Sunspot Number, F 10.7, CME Occurrence, EUV flux (24 -36 nm) and Flare Index with the monthly averaged values of Total Electron Content (TEC) at Usuda. We find that the TEC follows a synchronous variation with all the solar indices. The variation of TEC with Rz, F 10.7 cm and Solar EUV flux has more close agreement than with Flare Index and CME occurrence. The result is quite obvious since the primary source of ionospheric ionization is solar radiation flux. Moreover we also notice the solar indices and TEC follow an extraordinary agreement during the deep solar minimum of the cycle 24.

![Figure 1](image1.png)

**Figure 1.** Monthly variation of TEC with sunspot number, F 10.7, CME occurrences, EUV flux and flare index during solar cycle 23 and 24.

![Figure 2](image2.png)

**Figure 2.** Annual variation of TEC with sunspot number, F 10.7, CME occurrences, EUV Flux and flare index during solar cycle 23 and 24.

We further study the relationship of TEC with the solar activity indices using the yearly averages to get a smoothened pattern of variation between the two. The annual variation of TEC with Sunspot Number, Solar Radio Flux, CME occurrence, EUV Flux, and Flare Index is shown in Figure 2. The Figure 2 reflects the similar pattern as is observed in the Figure 1; however, the variation is smooth. The annual changes in the TEC at Usuda follow an extraordinary synchronization with the annual changes in solar activity. It shows that the long term variability of the solar activity is reflected in the
ionosphere very clearly. However, the variation of TEC is very much consistent with the annual changes in solar radiation flux than with other indices like CME occurrence etc. To quantify the association between long term solar activity indices and the TEC, we constructed the scatter plots and derived the correlation between the annual averages of solar indices and TEC. Figure 3 shows the scatter plot and correlation analysis between the yearly averaged values of TEC with Sunspot Number, F 10.7, CME occurrence, EUV flux and Flare Index during the solar cycle 23 and 24. It is quite evident from the Figure 3 that all the solar indices exhibit a strong correlation with the TEC at Usuda. We also calculated the correlation coefficients between all the solar indices and the TEC. The correlation coefficients of Sunspot Number, F 10.7, CME Occurrence, EUV flux (24-36 nm), and Flare Index with TEC are 0.99, 0.99, 0.76, 0.98 and 0.96 respectively. It shows that TEC almost follows one to one correlation with sunspot number, F 10.7, EUV flux (24-36nm) and flare index. However, the correlation of TEC with CME occurrences is comparatively lesser.

Then we divide the solar cycle into two parts namely ascending and descending phases. We also take the deep minimum of cycle 24 as ascending part of solar cycle 24. We obtained the correlation of TEC with each solar index during the two branches of solar cycle as well as during the deep minimum of cycle 24 separately. The correlation of each solar index with TEC for each case is shown in Figure 4. From the Figure we found that TEC exhibit a very strong correlation with all the five solar indices during both the phase of the solar cycle. The correlation between the two is also remarkable during the deep minimum of the cycle 24. The correlation coefficients of TEC with sunspot number, F 10.7, EUV flux (24-36 nm), flare index and CME occurrence are 0.98, 0.95, 0.97, 0.94 and 0.86 respectively during the ascending phase of the cycle 23. While during the descending phase of solar cycle 23 the correlation coefficients are 0.99, 0.99, 0.99, 0.96 and 0.57 respectively with sunspot number, F 10.7, EUV flux, flare index and CME occurrence. Here we notice that during the descending phase of the
cycle 23 the correlation with CME occurrence is weak. This is due to fact that during descending phase of the solar cycle the solar activity decreases due to which less number of CME are released from Sun and hence frequency of geomagnetic storms also decreases. Moreover the ionosphere behavior depends more on radiation flux than on geomagnetic storms. The correlation of TEC with sunspot number, F 10.7, EUV flux (24- 36 nm), flare index and CME occurrence are 0.99, 0.97, 0.99, 0.99 and 0.99 respectively. It is interesting to note that TEC follow a remarkable correlation with solar indices during the deep minimum of cycle 24. Another interesting feature we observe in the analysis is the hysteresis effect (Figure 4) which exists only with solar radio flux F 10.7 cm and EUV flux (24 – 36 nm). The hysteresis effect is completely absent with other solar indices like sunspot number, flare index or CME occurrence.

The high degree of correlations obtained for these solar activity indices suggest that the production and ionization of ionosphere and it dynamics is completely controlled by the level of solar radiance that is received by the ionosphere and the ionosphere closely vary with it. Therefore, the ionospheric variability will also follow the cyclic variability of solar activity. The least correlation achieved with CME occurrence indicate that it does not involve the radiations but the magnetic field.

4. Conclusions
From our study on the solar cycle variations of the ionospheric TEC we conclude our results as:

- The ionospheric TEC has a synchronized variation with the solar cycle. The TEC exhibits an excellent association with the solar radio flux F10.7 cm, Sunspot number, and Solar EUV flux indicating that which is more responsive to them than to Flare Index and CME occurrence.
- The variations of the TEC during the deep minimum of the cycle 24 i.e during 2007-2009 follow exceptionally high correlation with Solar radio flux and Solar EUV flux.
- The correlation of TEC with solar indices is stronger during the descending phase of the solar cycle than in the ascending phase.
- The TEC shows a hysteresis effect with solar radio flux F 10.7 cm and solar EUV flux (24 -36 nm) which is absent with other solar indices.

5. References
[1] Adler N O, Elias A G and Manzano J R 1997 Solar cycle length variation: Its relation with ionospheric parameters J. Atmos. Sol. Terr. Phys. 59(2) 159– 162.
[2] Klobuchar J A 1991 Ionospheric Effects on GPS GPS World 2 (4) 48-51.
[3] Kane R P 1992 Sunspots, solar radio noise, solar EUV and ionospheric foF2 J. Atmos, Terr. Phys. 54 463– 466.
[4] Kane R P 2003 Solar EUV and ionospheric parameters: A brief assessment Adv. Space Res. 32(9) 1713–1718.
[5] Lean J L et al 2001 Variability of a composite chromospheric irradiance index during the 11-year activity cycle and over longer time periods J. Geophys. Res. 106 10,645– 10,658.
[6] Bilitza D 2000 The importance of EUV indices for the International Reference Ionosphere Phys. Chem. Earth, Part C 25(5– 6) 515– 521.
[7] Rishbeth H and Garriott O K 1969 Introduction to Ionospheric Physics, Elsevier, New York.
[8] Kawamura S et al 2002 Annual and semiannual variations of the midlatitude ionosphere under low solar activity J. Geophys. Res. 107(A8) 1166, doi:10.1029/2001JA000267.
[9] Yu T et al 2004 Global scale annual and semiannual variations of daytime NmF2 in the high solar activity years J. Atmos. Sol. Terr. Phys. 66 1691– 1701.
[10] Balan N, Bailey G J and Jayachandran B 1993 Ionospheric evidence for a nonlinear relationship between the solar e.u.v. and 10.7 cm fluxes during an intense solar cycle Planet. Space Sci. 41(2) 141 – 145.
[11] Liu J Y, Chen Y I and Lin J S 2003 Statistical investigation of the saturation effect in the ionospheric foF2 versus sunspot, solar radio noise, and solar EUV radiation J. Geophys. Res. 108(A2) 1067, doi:10.1029/ 2001JA007543.
[12] Afraimovich E L et al 2008 Global electron content: A new conception to track solar activity *Ann. Geophys.* **26** 335–344.

[13] Balan N et al 1994a Variations of ionospheric ionization and related solar fluxes during an intense solar cycle *J. Geophys. Res.* **99** 2243–2253.

[14] Balan N, Bailey G J and Su Y Z 1996 Variations of the ionosphere and related solar fluxes during solar cycles 21 and 22 *Adv. Space Res.* **18**(3) 11–14.

[15] Kouris S S, Bradley P A and Dominici P 1998 Solar-cycle variation of the daily foF2 and M (3000)F2 *Ann. Geophys.* **16** 1039–1042.

[16] Lei J et al 2005 Variations of electron density based on long-term incoherent scatter radar and ionosonde measurements over Millstone Hill *Radio Sci.* **40** RS2008, doi:10.1029/2004RS003106.

[17] Liu L et al 2007 The dependence of plasma density in the topside ionosphere on solar activity level *Ann. Geophys.* **25**(6) 1337–1343.

[18] Mikhailov A V and Mikhailov V V 1995 Solar cycle variations of annual mean noon foF2 *Adv. Space Res.* **15**(2) 79–82.

[19] Rao M S J G and Rao R S 1969 The hysteresis variation in F2-layer parameters *J. Atmos. Terr. Phys.* **31** 1119–1125.

[20] Richards P G 2001 Seasonal and solar cycle variations of the ionospheric peak electron density: Comparison of measurement and models *J. Geophys. Res.* **106** 12,803–12,819.

[21] Sethi N K, Goel M K and Mahajan K K 2002 Solar cycle variations of foF2 from IGY to 1990 *Ann. Geophys.* **20** 1677–1685.

[22] Chakraborty S K and Hajra R 2008 Solar control of ambient ionization of the ionosphere near the crest of the equatorial anomaly in the Indian zone *Ann. Geophys.* **26** 47–57.

[23] Chen Y, Liu L and Le H 2008 Solar activity variations of night time ionospheric peak electron density *J. Geophys. Res.* **113** A1130 doi:10.1029/2008JA013114.

[24] Balan N, Bailey G J and Moffett R J 1994b Modeling studies of ionospheric variations during an intense solar cycle *J. Geophys. Res.* **99** 17,467–17,475.

[25] Gupta J K and Singh L 2001 Long term ionospheric electron content variations over Delhi *Ann. Geophys.* **18** 1635–1644.

[26] Soicher H 1988 Traveling ionospheric disturbances (TIDs) at mid-latitudes: solar cycle phase dependence *Radio Sci.* **23** 283–291.

[27] Van Velthoven P J 1990 Medium-scale irregularities in the ionospheric electron content Ph.D. Thesis, Technische Universiteit Eindhoven.

[28] Jakowski N, Schlüter S and Sardón E 1999 Total electron content of the ionosphere during the geomagnetic storm on 10 January 1997 *J. Atmos. Sol. Terr. Phys.* **61** 299–307.

[29] Tsurutani B T et al 2004 Global dayside ionospheric upliftment and enhancement associated with interplanetary electric fields *J. Geophys. Res.* **109** A08302.

[30] Chen Y, Liu L and Wan W 2011 Does the F 10.7 index correctly describe solar EUV flux during the deep solar minimum of 2007-2009 *J. Geophys. Res.* **116** A04304, doi:10.1029/2010JA016301.

[31] Luhr H and Xiong C 2010 IRI-2007 model overestimates electron density during the 23/24 solar minimum *Geophys. Res. Lett.* **37** L23101, doi:10.1029/2010GL045430.