Short term variability in foF2 and TEC over low latitude stations in the Indian sector

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Received 19 September 2014; revised received and accepted 16 February 2015

Since the ionosphere is a typical embedded plasma dominated region of the thermosphere, it may be of interest and relevance to study the association between the two different measured quantities, namely the peak electron density of the F2 layer (foF2) or the total electron content (TEC) of the ionosphere and thermospheric parameters. Both these parameters show a large variability during quiet and disturbed conditions as well as during the low and high sunspot periods. Simultaneous TEC (GPS) and foF2 (ionosonde) data obtained at a low latitude station, Waltair (17.72°N, 83.32°E) and a station, located at the inner-edge of the equatorial ionization anomaly (EIA), Delhi (28.58°N, 77.21°E) during the low sunspot period 2004-2005 (mean Rz = 38.55) have been considered for the present study. The Daubechies class of continuous wavelet analysis has been used in the present study to observe the variability in time. To test the efficacy of the correlation between the variability of foF2 and TEC, the cross correlation analysis has been made. An anti-correlation between the variability of foF2 and TEC is observed around noon hours over Waltair. The relative deviation (%) of day-to-day variability between foF2 and TEC is within the inter quartile range of 40.

Keywords: F2 layer electron density, Equatorial ionization anomaly (EIA), Total electron content (TEC), Correlation coefficient

PACS Nos: 94.20.dj; 94.20.dt

1 Introduction

The ionosphere and protonosphere collectively known as plasmasphere can be presumed as horizontally stratified. It is of importance to study the ionosphere for any period at any place as it shows a wide range of variability from place to place and time to time. It is highly variable because of various strong coupling processes. The variation of foF2 and TEC are not similar over a period of time. Further, the variability also depends on several factors such as season, sunspot activity, magnetic activity, etc. A better understanding of ionosphere variability leads to modeling and prediction purposes for low and high sunspot periods. The main source of variability in the ionosphere comes from charged particles and it responds to the neutral atmosphere as well in the thermosphere1.

The ionosphere responds to the thermospheric winds and these winds can push the free electrons along the inclined magnetic field lines to different altitudes away from the equator. The ionosphere also responds to the composition of the thermosphere, which affects the rate at which ions and electrons recombine. The ionosphere is a highly complex system and it acts as an intermediary between plasma dominated magnetosphere and bulk of neutral atmosphere. There exists a high correlation between parameters of lower and upper atmosphere2-4. The upward propagation of the atmospheric waves, like planetary or Rossby waves, tides and gravity waves are the main source of energy, which causes the variation of foF2 and TEC. The critical frequency of F2 layer (foF2) is the upper limit of high frequency vertical propagation and TEC (integrated electron density along the path of propagation), which is of important concern in trans-ionospheric communication should illustrate the electron density. It is also known that ionospheric electron density is a variable owing to energy coming from below as well as the equatorial electrodynamics, such as ExB drifts, which lead to equatorial ionization anomaly (EIA) and meridional winds.

As the electron density play a vital role in radio wave propagation, it is important to understand the behaviour of TEC and foF2 and correlation between their variability. The perturbation of electric
fields and thermospheric winds produce fluctuation in the E and F layers. These fluctuations are considered as the main cause of day-to-day variability in the ionospheric parameters. Several statistical studies have been made on the variability of foF2 and TEC. Among these studies, the correlation analysis is the most important method, which directly maps the two parameters. The greatest contribution to the TEC from the F-layer disturbance of the ionosphere is not only influenced by the significant changes in the solar and geomagnetic variations but also from the neutral wind effects. It has been revealed that the prediction of one of the parameters TEC/foF2 is possible if another one foF2/TEC is known. The foF2 only cannot be considered as the significant parameter to calculate the value of TEC, as TEC is the factor that depends on the ionosphere as well as the plasmasphere. To predict the TEC values, one must consider the plasmasphere in addition to ionosphere.

The degree of ionospheric disturbances and the physical mechanisms of the ionospheric variability were largely studied by several researchers. The degree of variability for high sunspot period is less when compared to that during the low sunspot period. Buresova & Lastovicka reported that there is a hysteresis relation between the sunspot variability and ionospheric variability. Further, Lamming & Cander used the monthly median values of foF2 along with month, local time and sunspot number (SSN) in predicting the foF2 values at a mid latitude station, Poitiers (46°N, 0°E), France. It is also difficult to predict the ionospheric variability at the disturbed ionospheric conditions as they vary significantly. The ionospheric parameters show high degree of variability during the geomagnetic storm conditions. During geomagnetic quiet conditions also, the ionosphere shows a high degree of variability due to the dynamics of lower atmosphere (tides, gravity waves and planetary waves). Prölls studied the morphology of storms and discussed about the possible mechanisms relating to the neutral - ion compositions, external electric fields and interaction between ionosphere and protonosphere and their variability.

Deviation of instantaneous value of foF2 or TEC from quiet reference is often taken as degree of the ionosphere disturbance. However, linear deviations from the quiet reference show disproportion of the scales of positive and negative deviations. The variability of TEC is not governed by exactly the same factors as foF2, since important contributors to the TEC are also the topside ionosphere and influences from the plasmasphere above the F2 region. If two parameters vary in a similar passion with time, one cannot predict one parameter with other. If the variability of two parameters has good correlation, then one can predict the parameters with each other. This is true mathematically. Applying this, two similarly varying parameters, like foF2 and TEC are considered and the correlation between them and their variability is calculated.

The variability of ionospheric parameters foF2 and the TEC are not, generally, correlated and their latitudinal behaviour as observed on two different stations shows a remarkable difference. Day-to-day variability of TEC does not follow the solar flux variation trend, which indicates the absence of any relation between TEC and solar radiation. TEC at any location is not a simple function of solar flux alone but varies with neutral winds, composition and electric field, which may contribute even more tides and waves since it is an integrated parameter. Further, transport by the equatorial fountain effect may also control its variability.

To check the periodicity of variability, the wavelet analysis has been made in the present paper. But there is no periodicity in the variability, which shows there is no correlation in their variability. In order to justify this, both correlation between foF2 and TEC as well as the correlation between variabilities of foF2 and TEC are also studied for low sunspot and geomagnetically quiet period. As expected, there is a good correlation between foF2 and TEC. But the variabilities of foF2 and TEC are not well correlated. This shows that it is impossible to predict the values of foF2/TEC using one another.

2 Data and Method of analysis
The differential time delay measurements on L1 and L2, transmissions from the GPS satellite are utilized to measure the total electron content (units of TEC are TECU and 1 TECU = 10^16 electrons m^-2) of the ionosphere and protonosphere between the satellite and a receiver at the ground. The Global Positioning System (GPS) uses coherently derived identical modulation on two carrier frequencies called L1 and L2 to measure the ionospheric group path delay directly and thereby corrected for ionospheric
time delay. The two carrier frequencies transmitted by the GPS system are the 154th (L1 = 1575.42 MHz) and 120th (L2 = 1227.60 MHz) harmonics of 10.23 MHz, which is bi-phase modulated on both carriers with pseudo random code of 10.23 MHz chip rate. As the modulation is transmitted with a known phase difference on two carriers, the received modulation phase difference is a direct measure of the ionospheric group path delay. The ionospheric group path delay at frequency L2 is:

$$\Delta t_2 = \frac{1}{2} \delta(\Delta t)$$

where, $$\delta(\Delta t)$$ is the difference between the ionospheric time delay measured at the two frequencies. This difference in the range is directly related to absolute ionospheric time delay as the satellite is in the same range at both the frequencies. Therefore, the measure of absolute TEC from the modulation phase delay at L2 minus L1 is:

$$\text{TEC} = 2.852 \times 10^{16} \times \delta(\Delta t)$$

where, $$\delta(\Delta t)$$ is measured in nanoseconds (ns).

The KEL ionosonde is used to measure the virtual height and critical frequency of the ionosphere. The Digital Ionosonde system (KEL Aerospace Pvt Ltd, Australia), installed at Waltair in the year 1989, consists of an IPS-42 (Ionospheric Prediction Service) ionosonde and a DBD-43 system dedicated to the IPS-42 with pre-programmed software, a double delta antenna and a hard copy printer. The IPS-42 consists of a transmitter, receiver and all necessary sub-systems. The DBD-43 is used for controlling the operational program of IPS-42, i.e. to store and scale the ionograms and to give commands for the printouts.

The ionosonde measured critical frequency, which is a partial measurement of electron density, should obviously correlate with the total electron content measured with the GPS. The method of cross correlation has been adopted as it is a standard method of estimating the degree to which two series are correlated. The cross correlation between the parameters TEC and foF2 as well as the variability of TEC and foF2 has been calculated. The variability has been calculated from the relation:

$$X_d - X_m$$

where, $$X_d$$ stands for hourly daily values; and $$X_m$$ stands for the corresponding monthly mean value of corresponding TEC and foF2 parameters. Continuous wavelet analysis has also been used to observe the variability at small scale levels of each individual parameter. Plotting the wavelet transform allows the picture to be built of correlation between wavelet at various scales and locations and the signal, thus, gives a two dimensional array of values, which is better than that of the Fourier Transform, which is one dimensional array of values. Mathematically wavelet is defined as:

$$w(a, b) = \int_{t} f(t) \frac{1}{\sqrt{a}} \psi\left(\frac{t-b}{a}\right) dt$$

where, $$a$$ is a scaling parameter; and $$b$$ is a location parameter. The continuous wavelet transform is the sum over all time of the signal multiplied by scaled, shifted versions of the wavelet. This process produces wavelet coefficients that are a function of scale and position.

Cross correlation analysis provides a correlation between two time series or two waveforms. By considering the two parameters foF2 and TEC and their corresponding variabilities, the observations of one series (foF2/TEC) are correlated with those of another series (TEC/foF2) at various lags and leads. Cross-correlation helps in identifying the variables, which are leading indicators of other variables or how can change in one variable be predicted in relation to the other. There are three possible outcomes, viz.: (i) positive correlation ($$r = +1$$), i.e. one variable rises and the other variable is predicted to rise at a similar rate; (ii) zero ($$r = 0$$) or no correlation; (iii) negative correlation ($$r = -1$$), i.e. one variable rises and the other falls. The cross correlation test of two time-series data sets involves many calculations of the coefficient $$r$$ by time-shifting one data set relative to that of the other. Each shift is called a ‘lag’, and the lag time is simply the sampling period of the data sets of two time-series. A typical cross-correlation with enough lags in both negative and positive directions shows the cyclic relationship between the two datasets. The cross correlation is calculated from the formula:

$$r = \frac{\sum [(x(i) - m_x) \cdot (y(i-d) - m_y)]}{\sqrt{\sum (x(i) - m_x)^2} \cdot \sqrt{\sum (y(i-d) - m_y)^2}}$$

where, $$m_x$$ and $$m_y$$ are the means of the corresponding series. If the above is computed for all delays $$d = 0, 1, 2, ..., N-1$$, then it results in a cross correlation series of twice the length as the original series.
In the present study, the cross correlation analysis for foF2 and TEC daily values of each month and for monthly mean values during the period March 2004 - February 2005 for a low latitude station, Waltair (17.72°N, 83.32°E) and a low mid latitude station, Delhi (28.58°N, 77.21°E) have been made. The locations of the two stations, Waltair and Delhi for the present period of observation are presented in Fig. 1. The period March 2004 - February 2005 is considered because it is the starting period of declining phase of the 23rd solar cycle and variability is high for a low sunspot period. Depending on Rz value, solar activity can be classified into low solar (Rz<40); moderate solar (40<Rz<80); and high solar (Rz>80) activity periods.

The simultaneous measurements of foF2 and TEC from the two different stations are used in this analysis to calculate their individual correlation and their variability correlation. Further, the relative deviations of the variability (TEC and foF2) and their quartiles have been studied to understand the variation from hour-to-hour of each day.

3 Results and Discussion

It is known that the variation of the foF2 and TEC, in general, depends on the season, sunspot and magnetic activities. With a view to examine the variability of foF2 and TEC over Waltair and Delhi, the data of two months, namely April and July 2004 are considered in the present study. The percentage of variability is calculated using Eq. (1) for the two individual parameters, foF2 and TEC and plotted for both the stations, Waltair [Fig. 2(a and b)] and Delhi [Fig. 3(a and b)] for the months of April and July 2004. The variability shows positive and negative values, which indicate the increase and decrease in the daily values with respect to monthly mean values. From these two figures, it is clearly observed that variability is high during both the months at two different stations.

Gulyaeva and Forbes et al. reported that deviations in foF2 and TEC from their instantaneous value, which is defined as the degree of ionospheric disturbance, never exceeds -100 and may be positive varying up to a value of 1000 during storm conditions. A large positive deviation in foF2 is observed in the present study over Waltair (around 90) during April and July and Delhi (around 140) only in April, while satellite measurements show more negative deviation (<-100) in some of the cases. The result obtained in the present study is in conformity with the result of Gulyaeva and Forbes et al. Jayachandran et al. reported that there is a good correspondence in the day-to-day variabilities of integrated electron content and peak electron density from one solar cycle to the other for both sunspot minimum and maximum.

The Daubechies class of continuous wavelet analysis has also been used in the present study to observe the variability in time. The wavelet analysis for the corresponding plots of Waltair [Fig. 2(a and b)] and Delhi [Fig. 3(a and b)] has been carried out and the plots are presented in Fig. 2(c and d) (foF2 in top panel and TEC in bottom panel) and Fig. 3(c and d) (foF2 in top panel and TEC in bottom panel), respectively. From these figures, it is generally observed that the variability (%) in foF2 and TEC is very high. In order to quantify the variability, wavelet analysis has been used. Wavelet analysis is a method to investigate signals that change over time. A wavelet is a waveform of effectively limited duration that has an average value of zero. Wavelet analysis is the breaking up of a signal into shifted and scaled versions of the original (or mother) wavelet. From these figures, it is observed that there is no periodicity in the variability of the given two parameters at a given time, which shows that there is no correlation between the variability.

Kouris et al. reported that the variability exhibits its greater values during night time hours when disturbed conditions usually prevail. The disturbance in the period of study was assessed using the Kp index and only three days are slightly geomagnetically disturbed in the month of July. (Kp>6).
Even though both TEC and foF2 are the representative parameters of electron density, the variations in foF2 are different compared to those in TEC. Lastovicka\textsuperscript{20} reported that there is a large temporal and partly spectral variability of planetary wave type activity at low latitude stations in the European sector. These fluctuations in TEC are related to fluctuations in the prevailing wind\textsuperscript{21}, while those in foF2 seem to be related to the fluctuations in the tidal winds\textsuperscript{20,22}.

3.1 Comparison of direct TEC and foF2 values and their correlation

The cross correlation test of two time series data sets foF2 and TEC involves many calculations of the coefficient (r) by time-shifting TEC data set relative to that of foF2. From the cross correlation analysis, the daily and monthly mean values of foF2 and TEC over Waltair and Delhi are presented in Fig. 4(a and b) and Fig. 4(c and d), respectively for the month of April 2004 as a stem plot. It is seen from these figures that the monthly mean correlation values of foF2 and TEC and daily values of foF2 and TEC show a good correlation. A similar result is also observed over Waltair [Fig. 5(a and b)] and Delhi [Fig. 5(c and d)] for the month of July 2004 as a stem plot. Figs (4 and 5) also indicate that there is a good correlation between foF2 and TEC values. Kouris \textit{et al.}\textsuperscript{19} from a mid latitude station in Italy reported that the linear correlation between TEC and \((\text{foF2})^2\) for daily values is lower than that of the monthly mean values and a hysteresis like variation is observed.

The correlation, thus, calculated for the two ionospheric parameters foF2 and TEC is high and hence, the impact of errors may transpire either in a positive or negative way. The errors may occur in TEC while converting STEC to VTEC and in
foF2 while taking real time scaling. The dual frequency receiver measures pseudo-ranges and carrier phases at L1/L2 frequencies and its observables are used to compute the TEC. The phase leveling technique\textsuperscript{23,24} is used to compute the precise phase derived slant TEC for each tracked satellite at each observation epoch. These slant TEC measurements are the sum of the real slant TEC, the GPS satellite differential delay $b_s$ (satellite bias) and the receiver differential delay $b_R$ (receiver bias). Therefore, the slant TEC can be expressed as:

$$s\text{TEC} = S(E) \times v\text{TEC} + b_R + b_s$$

where, $s\text{TEC}$, is the slant TEC measured; $E$, the elevation angle of the satellite in degrees; $S(E)$, the obliquity factor with zenith angle ($z$) at the ionospheric pierce point (IPP); and $v\text{TEC}$, the vertical TEC at the IPP. The sources of the uncertainties in scaling foF2 may be due to the uncertainty of the arrival directions of the reflected signals and uncertainty in sensing the ordinary and extraordinary modes. If the error occurred in both parameters of foF2 and TEC is either positive or negative, the resultant correlation is less and if one of it is positive and the other one is negative then the correlation is high. In general, in the present study, 5 - 10% error is observed in the computation of the correlation between foF2 and TEC.

3.2 Comparison between the variability of TEC and foF2 and their correlation

The correlation between the variability of the ionospheric parameters foF2 and TEC over Waltair and Delhi for the months of April and July 2004 is calculated and presented in Fig. 6. No significant correlation is observed between variabilities of foF2 and TEC at zero time lag over Waltair and Delhi during both the months, which support the results of
Fig. 4 — Cross correlation analysis of foF2 and TEC for the daily and monthly mean values over: (a and b) Waltair; and (c and d) Delhi, respectively for April 2004.

Fig. 5 — Cross correlation analysis of foF2 and TEC for the daily and monthly mean values over: (a and b) Waltair; and (c and d) Delhi, respectively for July 2004.
Figs 2 and 3. Using neural network forecasting of TEC, Xenos et al.\textsuperscript{25} reported that there is no correlation between the variability of foF2 and TEC but the normalized variability of foF2 and TEC parameters are well correlated. Further, Houminer \& Soicher\textsuperscript{9} explained that the correlation between foF2 and TEC variability is less during equinoctial months of high sunspot period of 1980 as there are more post sunset enhancements in TEC, which are absent in foF2. It has also been reported that the correlation is high for the remaining two seasons. Thus, the availability of global GPS constellation with instantaneous time delay, or equivalently, TEC values could provide an instantaneous updating of foF2 models on a global basis as well as on regional basis.

The diurnal variation of the foF2 and TEC variability correlation coefficients for all the months at both the stations is presented in Fig. 7. The correlation coefficient for each two hours duration is calculated as a result of four hour block (means correlation at 02:00 hrs LT is the resultant correlation of 00:00-04:00 hrs LT data and correlation at 22:00 hrs LT is the resultant of 20:00-00:00 hrs LT). From these figures, it is observed that the correlation is positive and maximum up to 10:00 hrs LT over Waltair and then suddenly becomes negative. An anti-correlation between TEC and foF2 variability is observed around 12:00 and 16:00 hrs LT. While the correlation between TEC and foF2 variability over Delhi is low at 04:00 hrs LT and is almost constant up to 12:00 hrs LT and then decreases. The deviations in the correlation between foF2 and TEC variability may be caused due to different factors like vertical drifts and equatorial electrojet strengths (EEJ). Houminer \& Soicher\textsuperscript{9} reported that the day time correlation between foF2 and TEC variability is higher than that of the night time for the mid latitude station, Cyprus (30.3°N, 28.9°E), Israel.

The cross correlation values of foF2 and TEC variability for each month at both the stations, Waltair and Delhi are presented in Figs. 8 and 9, respectively. From these figures, it is seen that the
correlation values are in general found to be less than 0.5, which means that there is no significant correlation between the variability of the two parameters foF2 and TEC. It is also observed that there is no consistent behaviour in the correlation values during the different months. Sethi et al.\textsuperscript{7} reported that the variability of foF2 is lower in the daytime hours than that in the night time during all the seasons of high sunspot period, while during low sunspot period, foF2 variability does not show any systematic diurnal pattern.

With a view to explain the statistical behaviour and characteristics of the hour-to-hour and day-to-day variability, the upper and lower quartiles of foF2 and TEC variability for all the months at both the stations Waltair and Delhi are computed and presented in Figs 10 and 11, respectively. From these figures, it is observed that the variability of foF2 lies almost within the range of the TEC. The variability between foF2 and TEC from hour-to-hour of each day lies within the inter quartile range of 40. Kouris & Fotiadis\textsuperscript{26} reported that the variability from day-to-day is greater than hour-to-hour in a number of stations for foF2. Furthermore, it has been reported that the relative deviations (positive or negative) are surrounded by 0.20 for 85 - 90\% of the time depending upon location, geographical zone and disturbances with high variability from day-to-day than hour-to-hour. The result obtained in the present study is in good agreement with the result of Kouris et al.\textsuperscript{19}.

Various researchers have reported on the ionosphere variability and its causes, but ionospheric behaviour (hour-to-hour and day-to-day variability of ionospheric parameters) awaits explanation and prediction in the framework of climatological, solar cycle and seasonal variations. To understand and possibly forecast the ionospheric variability, coupling from lower atmosphere needs to be considered. The energy densities in the troposphere and stratosphere are of several orders of magnitude greater than those in the thermosphere and a high amount of leakage of energy from lower atmosphere might in principle disturb the energy distribution in the thermosphere and affect the ionospheric behaviour\textsuperscript{24}.

Altadill et al.\textsuperscript{28} reported that the mechanisms that lead to planetary wave-like oscillations in the ionosphere are different from case-to-case and a direct link between neutral atmosphere and ionosphere cannot be provided in each case. Using the hourly values of foF2 data from three different Indian stations, Trivandrum (8.5°N, 76.8°E) and Kodaikanal (10.2°N, 77.5°E) located near the dip equator and Delhi (28.6°N, 77.2°E) located north of the equatorial ionization anomaly (EIA) during the high sunspot periods, Dabas et al.\textsuperscript{29} reported that the short and long terms variations in the observed daytime foF2 values are found to be unrelated to the solar and magnetic activity changes most of the time. The short as well as long term (seasonal/annual) variations in foF2 around the dip equator stations are found to be mainly controlled by the EEJ strength variations during the high sunspot periods. It has also been suggested that for equatorial and low latitude location, electrojet strength is a useful parameter for the prediction of day-to-day changes in the ionosphere as well
Fig. 8 — Month-to-month variation of correlation coefficients of foF2 and TEC variability over Waltair during 2004-2005

Fig. 9 — Month-to-month variation of correlation coefficients of foF2 and TEC variability over Delhi during 2004-2005
Fig. 10 — Variation from hour-to-hour of the each day over Waltair (upper and lower quartiles of foF2 and TEC)
Fig. 11 — Variation from hour-to-hour of the each day over Delhi (upper and lower quartiles of $f_0F_2$ and TEC)
as latitudinal distribution of plasma. Rastogi & Rajaram have also suggested that a strong electrojet should lead to a stronger E×B drift and ionization anomaly.

From the present study, it is seen that the correlation between foF2 and TEC variability is low and hence, it is difficult to predict TEC or foF2 using one another. This can be explained in terms of E×B vertical drift, equatorial ionization anomaly and equatorial electrojet strength around low latitudes and it is possible to develop a realistic ionospheric model.

4 Summary

The salient results obtained using the cross correlation analysis of the variability of foF2 and TEC parameters during low sunspot period are:
(i) The small scale variations are observed to be more in foF2 compared to those in TEC.
(ii) The correlation between the variability of foF2 and TEC is observed to be very low.
(iii) An anti-correlation between the variability of foF2 and TEC is observed around noon hours over Waltair.
(iv) The relative deviation (%) in their hour-to-hour of each day variability between foF2 and TEC is observed to be within the inter quartile range of 40.
(v) It is not viable to predict foF2 or TEC using one another.

Acknowledgement

The authors wish to express their sincere thanks to Dr R S Dabas, National Physical Laboratory, New Delhi for providing ionosonde data. One of the authors (PLS) wishes to express her sincere thanks to UGC for providing financial support through a minor research project.

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