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4 **Characteristics of Total Electron Content (TEC) observed from a chain of**
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7 **stations near the northern crest of the Equatorial Ionization Anomaly (EIA)**
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10 **along 88.5°E meridian in India**

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33 **Abstract:**
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36 The equatorial ionosphere presents some of the highest TEC values in the world coupled
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38 with observations of periodic structures. Total Electron Content (TEC) and scintillation data
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40 were analyzed from a chain of stations Calcutta (22.58°N, 88.38°E geographic; 32°N magnetic
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42 dip), Baharampore (24.09°N, 88.25°E geographic; 35°N magnetic dip) and Farakka (24.79°N,
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44 87.89°E geographic; 36.04°N magnetic dip) situated almost same meridian (88.5°E) during
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46 September 2011 and March-April 2012 for elevation greater than 20° so that the ionosphere can
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48 be tracked from the 15.50°N south of Calcutta to 31.80°N north of Farakka. Periodic variation of
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50 TEC was noticed before TEC bite out, predominantly within a particular latitudinal swath (19°N
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52 –26°N) along 88.5°E meridian. No periodic structures were observed over the magnetic equator
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54 during the observation period on ionosonde records from the magnetic equator station
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Trivandrum and COSMIC, GRACE and C/NOFS electron density measurements. The present paper reports, perhaps for the first time from the Indian longitude sector, confinement of such periodic structures in TEC primarily within a latitude swath of 19.00°N to 26.00°N almost along the same longitude of 88.5°E.

Keywords:

Total Electron Content, Scintillation, Periodic structure, Electron density.

1. Introduction:

The equatorial ionosphere continues to provide challenges to error-free communication and navigation through the processes of (1) the Equatorial Ionization Anomaly (EIA) and (2) equatorial ionospheric irregularities. While the phenomenon of EIA extends over major part of the day till about 22:00 LT, effects of equatorial ionospheric irregularities remain mainly confined to the local post-sunset to midnight time interval. Plasma irregularities in the night time equatorial F region; have been the subject of extensive experimental and theoretical investigations over the past decades (Fejer and Kelley, 1980; Kelley, 1989; Fejer, 1996). The irregularities manifest themselves as (i) plumes in radar backscatter maps, (ii) spread F in ionograms, (iii) bite-outs in Total Electron Content (TEC) (iv) rapid fluctuation in amplitude, phase and polarization of the satellite signal due to relative motion of satellite, ionosphere and receiver known as scintillation.

The evolution of ionospheric irregularities, leading to a wide range of scale sizes, seems to involve the operation of a hierarchy of multistep nonlocal plasma processes involving an interchange instability that includes the collisional and collision-less Rayleigh-Taylor and $E \times B$ instabilities and drift waves driven by coupled electrodynamic and neutral atmospheric processes

(Haerendel, 1973; Scannapieco and Ossakow, 1976; Ossakow, 1981; Zalesak et al., 1982; Keskinen et al., 1998, Sekar and Kelley, 1998; Basu and Coppi, 1999). In the nonlinear regime the instability evolution process leads to the development of irregularities in the form of plasma depletions or bubbles (Woodman and LaHoz, 1976; Scannapieco and Ossakow, 1976). The bubbles so generated steepen on their top, get polarized, and rise to the top side of the ionosphere through enhanced electrodynamic drift (Ossakow and Chaturvedi, 1978; Anderson and Haerendel, 1979). By this mechanism it is possible to explain how the ESF irregularities could occur both in the bottom side and topside of the F region.

The prediction of post-sunset development of irregularities (ΔN) in plasma density (N) is difficult due to the day-to-day variability of the ionosphere. Reliable forecasting of the various manifested effects constitutes one of the main outstanding issues before the ionospheric scientific community. Pre-reversal enhancement (PRE) of the eastward electric field is an important factor to decide the generation of ionospheric irregularities. But in order to explain the day to day variability of scintillation occurrence factors other than PRE are needed (Hysell and Burcham, 2002; Tsunoda, 2005; Ray et al., 2006). During seasons of high occurrence probability of scintillation at a given location, scintillation might be absent on some nights, even when the strength of PRE is similar to that of the night when scintillation is present. Identification of precursors to onset of scintillations forms an important component of the international CAWSES (Climate and Weather of Sun Earth System) program.

The main contribution of Total Electron Content (TEC) (which is the integrated electron density along the path from satellite to receiver), comes from the electron density around the height of maximum ionization ($h_m F_2$). Any periodic signature in TEC implies propagation of the periodic perturbations at least up to the height of maximum ionization. In other words, for

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4 occurrence of scintillations, the undulating large-scale ionospheric perturbations should
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6 propagate to the height of maximum ionization and beyond (DasGupta et al., 2008). Ray et al.
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8 (2006) predicted the occurrence of equatorial ionospheric irregularities where as day-to-day
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10 variability and its corresponding characteristics are well described by Basu et al., (2009). Bagiya
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12 and Sridharan (2011) showed that variations of GPS Total Electron Content (TEC) with respect
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14 to TEC are considered to represent the seed perturbations for the plasma instability that results in
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16 equatorial spread F (ESF).
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21 Multi-point sensing of the ionosphere ensures understanding the spatio-temporal
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23 evolution of the irregularities primarily generated over the magnetic equator to off-equatorial
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25 locations. With a latitudinal network of distributed GPS receivers operating within Colombia,
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27 Peru and Chile with sufficient latitudinal span, Valladares et al. (2004) measured the absolute
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29 Total Electron Content (TEC) at both crests of the equatorial anomaly and the latitudinal
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31 extension of GPS scintillation. Valladares and Chau (2012) showed TEC perturbations
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33 associated with Travelling Ionospheric Disturbances (TID) over South America from the Low
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35 latitude Ionospheric Sensor Network (LISN). DasGupta et al. (2008) and Das & DasGupta
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37 (2012) found periodic structures in TEC before the bite out using TEC data from GAGAN
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39 stations in India. Thus occurrence of periodic structures in TEC prior to bite outs is an
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41 established result.
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48 Main objective of the present paper is to study the zone of occurrence of periodic structure
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50 in TEC before the onset of scintillation observed from a chain of stations along same meridian
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52 (88.5°E) from eastern part of India.
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2. Methodology:

The stations used for the multi station GPS campaigns of 2011 and 2012 were Calcutta (22.58°N, 88.38°E geographic; 32°N magnetic dip), Baharampore (24.09°N, 88.25°E geographic; 35°N magnetic dip) and Farakka (24.79°N, 87.89°E geographic; 36.04°N magnetic dip) there by providing coverage from 15°N to higher latitudes around 31.8°N. During the multi station campaigns, Slant Total Electron Content (STEC) and amplitude scintillation index S_4 are measured for the periods of September 2011 and March–April 2012 from two dual–frequency GPS receivers, one situated at Calcutta, near the northern crest of the EIA and the second one at (i) Baharampore during September 2011 and (ii) Farakka during March-April, 2012, situated beyond the northern crest of EIA along the same meridian (88.5° E).

Figure 1 shows the 20° zone of reception of GPS satellite signals from the three stations Calcutta, Baharampore, and Farakka, on a map of India. Combining the data for two stations at a time a) Calcutta, Baharampore and b) Calcutta, Farakka lying almost along the same meridian (~88.5°E) within 20° zone of reception, the ionosphere can be tracked from 15.50°N, south of station Calcutta to 31.80°N, north of station Farakka.

During September 2011, dual-frequency GPS measurements have been carried out from two stations Calcutta and Baharampore. S_4 at L–band and Vertical Total Electron Content (VTEC) were examined from each station for all satellite passes for an elevation greater than 20° over the whole sky i.e., all azimuth angles with 1 minute sampling interval. To determine the zone of reception, the 350–km subionospheric latitude and longitude were calculated from each station above an elevation 20° to eliminate the multipath effect and range rate error of the GPS signal. The zone of reception is bounded by the 350–km subionospheric points at 31.08°N,

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4 88.25°E in the north, 22.41°N, 95.94°E towards the east, 15.59°N, 88.39°E in the south and
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7 23.88°N, 80.61°E due west. If S_4 is greater than 0.2 in any satellite pass, VTEC are plotted to
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9 observe the TEC bite-outs associated with scintillation. The observed VTEC was subject to 90
10 minute moving average to eliminate any slow fluctuation due to spatial movement of satellite.
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12 The moving average of TEC was done from 18:00LT (LT=UT+6hr) up to the starting time of the
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14 onset of TEC bite out. The deviation of TEC was calculated by taking the difference between
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16 measured and average TEC during this time interval.
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21 Similar operation was performed during March–April 2012 from the stations Calcutta and
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23 Farakka. In this campaign period, all satellite links were tracked over the zone of reception (at
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25 350 km ionospheric height) from 31.78°N, 87.89°E in the north to 15.59°N, 88.39°E in the
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27 south and from 24.58°N, 80.21°E due west to 22.41°N, 95.94°E towards east taking the 20°
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29 mask angle for elevation.
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33 Constellation Observing System for FORMOSAT Satellite 3 [FORMOSAT-
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35 3/COSMIC or F3/C] electron density data is used to observe the N_mF_2 and H_mF_2 profile over
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37 Indian longitude sector during the experiment. In this study “ionPrf” level 2 vertical profile
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39 electron density data and “msl_alt” level 2 height profile data are obtained from CDAAC
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41 website (<http://www.cosmic.ucar.edu>) during September 2011 and April 2012 for the region
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43 bounded by -10°N to 35°N and 75°E to 95°E during 16:00–21:00 LT.
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48 In a similar fashion, from GRACE (Gravity Recovery And Climate Experiment) mission,
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50 “ionPrf” level 2 vertical profile electron density data along with “msl_alt”, the level 2 height
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52 profile data have been used to interpret the periodicity observed in VTEC,
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54 obtained from CDAAC website (<http://www.cosmic.ucar.edu>) during September 2011 and
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4 April 2012 for the region bounded by -7°N to 8°N geographic latitude where the geographic
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6 longitudinal spread was 82°E to 117°E.
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9 In the present study, IGS Total Electron Content (TEC) data obtained from SOPAC
10 website (<http://sopac.ucsd.edu/>) for two stations, Bangalore (77.68°N Latitude, 12.95°E
11 Longitude, 11.69°N magnetic dip) and Hyderabad (78.47°N Latitude, 17.44°E longitude, 21.9°N
12 magnetic dip) of India, are considered to validate periodic structure in TEC at locations near the
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14 magnetic equator and in between the magnetic equator and northern crest of EIA during
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16 September 2011 and April 2012.
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23 To validate the occurrence of periodic structure in VTEC observed from Calcutta and
24 Baharampore at September 2011, C/NOFS (Communication and Navigation Outage Forecast
25 System) vertical component of ion velocity (V_z) data is also analysed, obtained from the CINDI
26 website (<http://cindispace.utdallas.edu/>) with a sampling interval of 1 second, to check whether
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28 this structure is generated at the magnetic equator or not. Similar exercise has been performed for
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30 April 2012 by using the ionosonde data recorded from the magnetic equator station Trivandrum
31 (8.48°N, 76.94°E geographic; 0.3°S magnetic dip). The recorded ionosonde data contains $h_m F_2$,
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33 $h'F$ and $f_o F_2$ with a sampling interval of 7 minutes and the value of $N_m F_2$ can be calculated from
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35 $f_o F_2$ as
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$$N_m F_2 = 1.24 \times 10^{10} (f_o F_2)^2$$

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46 where the unit of $N_m F_2$ is m^{-3} and the unit for $f_o F_2$ is MHz (Pavlov and Pavlova, 2009).
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3. Results

During 24 days of common observations in September 2011 between the stations Calcutta and Baharampore, TEC and scintillation (S_4) data were observed in regular basis. From these observations there were 8 cases, where periodic variations of TEC were found prior to the onset of TEC bite out from Calcutta. Those cases were found on September 1st (SV12), 15th (SV2), 19th (SV29), 22nd (SV29), 23rd (SV25), 24th (SV26, SV29) and 25th (SV29), 2011 respectively from Calcutta. Similarly from Baharampore during September 2011, 5 cases of periodicity in TEC were found on September 1st (SV12), 15th (SV2), 23rd (SV25) and 24th (SV25, SV29), 2011 respectively. Information about the periodic structures of TEC found through the month of September 2011 and March-April 2012 are listed in Table 1.

The four panels in Figure 2(a) from top to bottom show the plots of VTEC, 90 minute moving average of VTEC, deviation of VTEC from the 90 minute moving average and S_4 index recorded on SV25 link on September 23, 2011 from Calcutta during 10:00 to 14:30 UT, above an elevation angle greater than 20° . Respective subionospheric latitudes and longitudes of the satellite pass are also mentioned along the x axis in the plot. It is found that at 13:27 UT, a deep bite out in TEC of 10.23 TECU was generated around 19.07°N , 83.71°E subionospheric respectively as shown in the topmost panel in the figure. Corresponding to the bite-out in TEC, scintillation was observed on this particular link. Before the occurrence of bite-out, periodic variation of VTEC was found as shown in the 3rd panel which is indicated as a circular mark with maximum peak to peak amplitude of 1.94 TEC units and duration of about 1 hour (12:00 to 13:00 UT). Figure 2(b) represents similar four plots for SV25 link on September 23, 2011 from Baharampore through the whole tracking period 10:00 to 14:45 UT, with an elevation angle greater than 20° . In this figure, it is observed from the topmost panel at about 13:31 UT, a deep

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4 TEC bite out in TEC of 9.82 TECU was formed around 20.07°N, 83.36°E subionospheric
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6 respectively. Corresponding to the bite out in TEC, intense scintillation ($S_4 > 0.6$) was observed
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8 on the SV25 satellite link. Before the occurrence of TEC bite-out, periodic variation of VTEC
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10 was found from the plot of TEC deviation (3rd panel) which is marked by 'black circle' with
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12 maximum peak to peak amplitude of 1.85 TEC units and duration of 1 hour 10 minute (12:00 to
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14 13:10 UT). To calculate the periodicity of those corresponding wave like structures observed in
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16 VTEC deviation, wavelet power spectrum have been performed over those wave like structures
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18 observed on SV25 link on September 23, 2011 from Calcutta and Baharampore shown in figure
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20 2(c) and 2(d) respectively. In figures 2(c) and 2(d), x axis represents the time of occurrence of
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22 wavelike structures in minutes and y axis for the periodicity of those wavelike structures in
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24 minutes. In figure 2(c) the periodicity of the corresponding wave like VTEC deviation is 50
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26 minutes. Similarly from figure 2(d), the periodicity of recorded wavelike structure from
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28 Baharampore at 23rd September, 2011 is 20 minutes.
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36 Table 2 demonstrates the detailed information about the occurrence, ~~their~~ wavelengths
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38 and periods of periodic structures on the SV25 link found from both Calcutta and Baharampore
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40 station on September 23, 2011. The spatial extent of the periodic structure observed by SV25
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42 from both stations is in this table calculated by considering the differences between the
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44 subionospheric latitude of the two adjacent trough and crest.
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48 To find out the presence of periodicity in VTEC before the onset of scintillation/TEC bite
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50 out on that particular day towards south of Calcutta or near/over the magnetic equator, electron
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52 density and data recorded by C/NOFS and two satellite constellations COSMIC, GRACE are
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54 been studied.
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Figure 2(e) represents the plot of electron density and its corresponding height profile or altitude as a function of local time, geographic latitude and longitude obtained from COSMIC data during 18:26 to 19:20 LT from 10.02°S to 11.26°N geographic latitude over the geographic longitude swath of 81.23°E to 91.57°E on September 23, 2011. It is observed that neither electron density depletion nor any wave signatures were developed near or over the magnetic equator, which can be observed towards north in later evening hours. Figure 2(f) demonstrates the same for GRACE constellation with an interval of 16:50 to 17:17 LT from 4.01°N to 8.00°N geographic latitude over the geographic longitude range of 82.27°E to 89.87°E on September 23, 2011. No electron density depletions or wave signatures were noticed near or over the magnetic equator which can be viewed towards the north later. Analyzing vertical component of ion velocity (V_z) from C/NOFS satellite passes on September 23, 2011, figure 2(g), it is found that the satellite passed nearly over the 78°E longitude sector when it crossed the magnetic equator around 9:15 MLT (MLT is nearly equal to LT). But at 18:00 LT (~12:30 UT) or after periodic variation of TEC is noticed from the three stations, there are no C/NOFS satellite passes available. During this time C/NOFS satellites passed over the southern hemisphere. From the station Calcutta, the periodic structure in TEC was observed during 18:00 LT (12:30 UT) at about 23.00°N subionospheric latitude; so it seems that the source of the occurrence of this undulation may be localized as evident from absence of depletions in both the COSMIC and GRACE and C/NOFS plots. Also the data recorded from the IGS (International GNSS Service) stations, Bangalore and Hyderabad, did not show any periodicity in TEC, which in turn confirms that the occurrence of the periodic structure of TEC which was observed from Calcutta and Baharampore may have generated locally for this case.

The 350 km subionospheric tracks of GPS satellites which showed periodic variation of TEC prior to TEC bite out within a subionospheric longitude swath of 80.00°E to 95.00°E observed from both Calcutta and Baharampore during the month of September, 2011 are represented in Figures 2(h) and 2(i) respectively. In these particular plots, the x axis represents the 350 km subionospheric longitude and the y axis provides 350 km subionospheric latitude for both Calcutta and Baharampore respectively. The points marked by 'black filled circle' in each satellite track, indicate the region of occurrence of periodic fluctuations of TEC. It is observed from these figures that, for most of the cases of occurrence of periodicity in TEC prior to the occurrence of TEC bite-outs, this periodic structure was noticed primarily only within a narrow latitudinal swath of 19.00°N to 26.00°N respectively, although combining the data of three stations, ionosphere can be tracked from 15.50°N to 31.80°N subionospheric latitude with a cut off of elevation around 20°. It is to be noted that the number of satellite tracks presented in both the Figures 2(h) and 2(i) are less than the number of cases of periodic structures in TEC, observed from both the stations Calcutta and Baharampore respectively mentioned in Table 1. This is because the tracks of the same satellites for two or more consecutive days nearly overlap with each other plot. Similar situation happened in Figure 2(i), where from Baharampore, SV25 recorded such periodic structures in TEC on 23rd and 24th September, 2011.

On September 19, 2011 from the station Calcutta SV21 recorded scintillation around 18:00 UT, no periodic structures of TEC were found before the onset of scintillation/ bite out. Similarly on 23rd September 2011, SV18 and on 24th September 2011, SV24 recorded similar kind of activity around 14:00 UT and 16:00 UT respectively. No cases have been observed during September 2011, where any SV link records the periodic variation in VTEC without affected by any scintillation.

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7 In the same manner, during the vernal equinox (March-April) of 2012, TEC and
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9 scintillation data were recorded from two stations Calcutta and Farakka simultaneously, situated
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11 along the same meridian ($\sim 88.5^\circ\text{E}$). Out of 44 days of common observation from the both
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13 stations, nine cases of occurrence of periodic structures in VTEC prior to bite out were recorded
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15 from Calcutta. Those nine cases were observed on April 01, 2012 (SV7, SV13 and SV23), April
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17 10, 2012 (SV13), April 17, 2012 (SV7), April 19, 2012 (SV7) and finally April 28, 2012 (SV1,
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19 SV7 and SV8) respectively. Similarly from the station Farakka, seven such cases of occurrence
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21 of periodicity in VTEC prior to bite out were recorded. Those cases were observed on April 01,
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23 2012 (SV13), April 9, 2012 (SV13), April 10, 2012 (SV13), April 19, 2012 (SV7), April 28,
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25 2012 (SV8) and April 30, 2012 (SV7, SV8) respectively.
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31 Figure 3(a) shows a four panel representative case study on April 19, 2012 recorded from
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33 the station Calcutta of SV7 link throughout the whole tracking period (10:00 to 16:30 UT), above
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35 an elevation angle of 20° . It is found that at 15:11 UT, a deep bite out in VTEC of 10.86 TECU
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37 was formed around 20.42°N , 89.83°E subionospheric as shown in the topmost panel of the
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39 figure. Before the occurrence of TEC bite-out, periodic variation of VTEC was found as shown
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41 in the 3rd panel which is marked as a circle with maximum peak to peak amplitude of 2.61 TEC
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43 units and duration of about 1 hour 50 minutes (13:10 to 15:00 UT). Figure 3(b) presents similar
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45 plots recorded from Farakka on the SV7 link on April 19, 2012 during the time interval of 10:22
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47 to 17:00 UT with an elevation greater than 20° . From the plot in the top most panels, a deep bite
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49 out in VTEC of 8.6 TECU was observed on 15:41 UT at around 20.73°N , 89.89°E
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51 subionospheric point along with the occurrence of scintillation on that particular SV link. Before
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53 the occurrence of the VTEC bite-out periodic fluctuation of VTEC was observed as shown in the
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3rd panel of Figure 3(b), which is indicated as a circle with maximum peak to peak amplitude of 2.89 TEC units and the duration of about 1 hour 38 minutes (12:06 to 13:44 UT). Figures 3(c) and 3(d) respectively represents the wavelet power spectrum of the wavelike structures of VTEC deviation prior to the bite out observed from Calcutta and Farakka during 19th April 2012 on SV7 link. In those figures x axis represent the time of occurrence in minutes and y axis provide the measurement of periodicity in minutes. From figure 3(c), it can be mentioned that the periodicity of the wavelike structure observed from Calcutta is 97 minutes where as from figure 3(d), the periodicity of the wave like structure recorded from Farakka is 145 minutes.

Table 2 provides information about the periodic variation in VTEC before the onset of scintillation on SV7 link, recorded from both Calcutta and Farakka on April 19, 2012.

Figure 3(e) shows the plot of electron density and its corresponding height profile as a function of local time, geographic latitude and longitude observed using COSMIC during 15:36 to 16:26 LT from 24.85°N to 27.81°N geographic latitude over the geographic longitude swath of 75.37°E to 87.57°E on April 19, 2012. It is observed that no electron depletions on wave signatures were developed along the satellite pass. But two hour later, around 12:00 UT (~ 17:47LT) periodic variation of VTEC was observed over the same region. From Calcutta, the periodic structures in VTEC were observed during 18:00 LT (12:00 UT) at about 25.67°N subionospheric latitude. Figure 3(g) represents four panel diagram of ionosonde data recorded from Trivandrum on that day. In the plot the first panel represents the variation of $N_m F_2$ with UT, and the other three shows the variations of $h_m F_2$, $h'F$ and $f_o F_2$ respectively with UT. As Trivandrum is situated near the magnetic equator, so efforts has been made to find out any undulation in electron density observed from this station during the time period of 12:00-15:00 UT since at this interval the periodic structure in VTEC has been recorded from Calcutta and

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4 Farakka. From the Figure it can be seen that during that period of time no such periodic
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6 structures in $N_m F_2$ has been recorded by ionosonde near the magnetic equator. Thus it seems that
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8 the source of the occurrence of this undulation may be localized as evident from absence of
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10 depletions in COSMIC, GRACE and ionosonde plots. Also the data set recorded from the IGS
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12 (International GNSS Service) stations Bangalore and Hyderabad, did not show any periodicity in
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14 TEC, which in turn confirms that the occurrence of the periodic structure of TEC which was
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16 observed from Calcutta and Farakka were generated locally.
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21 The 350 km subionospheric tracks of GPS satellites which showed periodic variation of
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23 TEC with subionospheric latitude prior to the TEC bite out within a subionospheric longitude
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25 swath of 75.00°E to 95.00°E observed from both Calcutta and Farakka station during the month
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27 of March-April, 2012 are presented in Figures 3(h) and 3(i) respectively. In these plots, the x
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29 axis represents the 350 km subionospheric longitude and the y axis for 350 km subionospheric
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31 latitude for both stations Calcutta and Farakka respectively. The points marked by 'black filled
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33 circle' in each satellite track, indicate the region of occurrence of periodic fluctuations of TEC. It
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35 is observed from those figures that, most of periodic structures in TEC were noticed only within
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37 a latitudinal swath of 19.00°N to 26.00°N respectively in Figure 3(h).
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43 In the vernal equinox of 2012, while analyzing all the cases of occurrence of TEC bite-
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45 outs and scintillation on all the satellite tracks, some cases were found where there were no
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47 periodic structures in TEC before the occurrence of TEC bite out. From station Calcutta there
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49 were ten cases observed during March-April 2012 and two from Farakka.
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4. Discussions:

In spite of extensive research on ionospheric physics for well over six decades, interesting results still continue to emerge that require realignment of present understanding of the background physical processes in the equatorial ionosphere. Observations of the periodic structures in TEC prior to the occurrence of depletions and occurrence of ESF and scintillations have been reported by several workers (Kelly et al., 1981, 1986; Hysell et al., 1990, 2006; Rottger, 1973, 1976, 1978; Vadas and Fritts, 2006; Vadas, 2007). DasGupta et al. (2008) discussed the observations of periodic structures in the phase records of an interferometer observing a radio star prior to the occurrence of ionospheric scintillations and correlated the results with GAGAN GPS measurements from a single station. Several theories have been proposed as to the source of such perturbations. The seeding mechanism can be developed from some local instability growth mechanism, for example, the wind driven instability of the bottom side F layer to serve as a seed perturbation to topside bubble development, as proposed by Kudeki et al., (2007). Hysell and Kudeki (2004) suggested that velocity shear mechanism at the F layer bottom side could be one of the triggering mechanisms for the development of ESF. The possible roles of sporadic E layer instability mechanism for initiating the conditions for ESF development are discussed by Tsunoda (2007) and Cosgrove and Tsunoda (2002). More recently an important source of ESF day-to-day variability has been shown to arise from planetary wave modulation of the evening pre-reversal enhancement in the zonal electric field (PRE) vertical plasma drift (Abdu et al., 2006). Sridharan et al. (2012) recorded the TEC data from a single satellite during 15:00-17:00 LT and took the difference between the actual TEC and the smoothed TEC. They found the periodicity of the fluctuation in the range of 15 minute to 60 minute by performing wavelet analysis, which falls in the category of gravity waves.

But the latitudinal confinement of the periodic structure of VTEC prior to the occurrence of bite out over a certain longitude swath ($\sim 88.5^\circ$) is unique in nature. This study reports perhaps for the first time from India, observation of the periodic structure in TEC before the occurrence of TEC bite-outs within a certain latitude zone. Considering 20° elevation mask angle, from the three observing stations at Calcutta, Baharampore and Farakka, the ionosphere can be tracked from 31.78°N , 87.89°E in the north to 15.59°N , 88.39°E at south. From the recorded cases of occurrence of periodic structures during the month of September, 2011 and March-April, 2012 it was observed that most of the cases of occurrences of periodicity (17 out of 29) were recorded within 19.00°N to 26.00°N almost along the same meridian (88.5°E). The ionospheric irregularities developed over the magnetic equator follow the magnetic field lines and extend to higher latitudes. There is a confinement of most of periodic structures in TEC during September, 2011 and March-April, 2012 between 19°N to 26°N , though the ionosphere was tracked from 15.5°N to nearly 32°N . It is important to note that the region around the northern crest of the EIA also experiences some of the most intense scintillations in the Indian longitude sector (Das et al., 2014). Hernández-Pajares et al., (2012) also observed that several of the main MSTID climatological trends at mid latitude are also shared at low and high latitude, and modulated in intensity and the solar cycle with typical wavelength of 100–300 km. Since the periodicities of VTEC as given in Table 1 are coherent with the periodicities of those MSTIDs/LSTIDs, so MSTIDs/LSTIDs could be one of the reasons for observing such periodic structure in TEC before scintillation. The low latitude equatorial ionosphere plays a dominant role in the transionospheric satellite signal propagation. The ambient ionization in this region is very high. The equatorial ionosphere and thermosphere constitute a coupled system, with its electro-dynamical and plasma physical processes being responsible for a variety of ionospheric

phenomena particular to the equatorial region (Abdu, 2001). The observed structures in TEC occurred around the northern crest of the EIA.

Another important issue for the wave like periodic structures is their spatial extent. In case of 23rd September, 2011, SV25 recorded wave structures from both Calcutta and Baharampore stations. From Table 2 it can be easily calculated that the spatial extent of the periodic structure observed along the track of GPS SV25 from station Calcutta was 273.9 km where as from Baharampore the wave structures covered 212.1 km spatial extent during its occurrence and the corresponding calculated periodicity of the wavelike structures observed from Calcutta and Baharampore are 50 minutes and 20 minutes. Similarly during 19th April, 2012 SV7 records periodic structures from both Calcutta and Farakka with the total spatial extent observed from Calcutta being 388.3 km and 529.1 km from Farakka respectively. The periodicity of the wavelike structures recorded from Calcutta and Farakka on 19th April 2012 are 97 minutes and 145 minutes respectively. Table1 represents the full statistical analysis of the periodicity observed in VTEC deviation prior to bite out during the month of September 2011 and April 2012. The ranges of periodicity achieved in this analysis are found to be 20 minutes to 145 minutes.

Tsunoda et al. (2011) showed that routine observations of Total Electron Content (TEC) measured as a function of latitude and longitude provides information of LSWS (Large Scale Wave Structure). Abdu et al. (2015) also demonstrated the effect of large-scale wave structure in the equatorial ionospheric *F* region that serves as precursor to post-sunset development of the spread *F* plasma bubble irregularities. Small amplitude oscillations in the *F* layer heights, extracted at a number of plasma frequencies, present characteristics as them being generated from upward propagating gravity waves. They represent wave structures in polarization electric

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4 field having zonal scale of a few hundred kilometres. LSWS has the zonal wavelength of
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6 500–700 km spread over a wide longitudinal range. But in the present investigation since the
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8 stations are situated nearly along the same meridian, any undulation in TEC before bite out
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10 essentially has spread over latitude. Thus the periodicity of TEC prior to the bite out observed
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12 from a meridional chain of stations located around the northern crest of EIA, has a strong
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14 latitudinal dependence and is a new finding in ionospheric dynamics reported in this manuscript
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16 perhaps from the first time over the Indian longitudinal sector. It has been reported earlier that
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18 LSWS (Large Scale Wave Structure) has a zonal wavelength of nearly 500 to 700 km (Thampi et
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20 al., 2009; Tulsi Ram et al., 2012) where TEC variation along meridional direction is smaller than
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22 the zonal direction. But in the present investigation the latitudinal variation of TEC is dominant
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24 over longitudinal variation since all the stations are located along the same meridian and the
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26 distance traversed by these wavelike structures are also small.
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33 From COSMIC and GRACE electron density plots on September 23, 2011, fluctuations in
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35 electron densities were not noticed throughout their pass near magnetic equator located south of
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37 both the stations Calcutta and Baharampore, during afternoon to sunset hour. C/NOFS vertical
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39 ion velocity is also analysed to find whether the undulation is formed over magnetic equator or
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41 not. But there is no pass during 12:00 UT on the magnetic equator over the Indian longitude
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43 sector. IGS stations Bangalore and Hyderabad also noticed no occurrence of periodic TEC
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45 variation prior to bite out during the time interval on SV links which are located south of both
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47 Calcutta and Baharampore. So the source of TEC undulation may be generated locally.
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53 During April 19, 2012 no fluctuation in electron density was found during the pass of
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55 COSMIC satellite over $25^{\circ}\text{N} - 27^{\circ}\text{N}$ and $75^{\circ}\text{E} - 87^{\circ}\text{E}$ during 15:36 – 16:26 LT. The maximum
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57 electron density was observed near 27.3°N , 85.56°E . The undulation in TEC was observed on
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4 the same day during 12:00-15:00 UT (18:00–21:00 LT) over 25.67°N, 20.67°N latitudinal
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6 interval. There is no signature of undulation in the plots of $h_m F_2$, $h'F$ and $f_o F_2$ observed from
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8 Trivandrum on the same day. The maximum height of the F_2 layer also did not reach greater
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10 height which is generally observed during ESF. Also the IGS stations Bangalore and Hyderabad
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12 did not found any TEC variation prior to the bite out during this time interval. GRACE satellite
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14 which was passing near magnetic equator during afternoon hours did not encounter any variation
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16 in electron density. No C/NOFS pass was found during this day whose location and timing
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18 matches with the TEC observations.
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24 From the Figures 2(h, i) and 3(h, i) the facts to be noted are that the zone of occurrence of
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26 periodic structures closely correspond to the zone of the intense scintillation occurrence around
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28 the northern crest of the EIA in the Indian longitude sector. However ionospheric irregularities
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30 which impact transionospheric satellite links at Calcutta are normally expected to develop over
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32 the magnetic equator and then elongate along highly conducting magnetic field lines to off
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34 equatorial locations. For the stations at Baharampore and Farakka which are located beyond the
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36 northern crest of EIA, cases of drifting ionospheric irregularities of mid-latitude origin affecting
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38 GPS links at those stations have been reported in literature (Das et al., 2014).
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44 It is also suggested that the F-region zonal winds are the source of the electric fields
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46 which in turn drive the ion drifts at low latitudes and control the scintillation activity. Pedersen
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48 conductivity and shear in the neutral wind are responsible for the latitudinal gradient of the drift
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50 velocity of the irregularity bubbles. The latitudinal and temporal variation of the zonal drift
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52 velocity of the bubbles (Pimenta et al., 2003; Makela, 2006) may be one of the factors for the
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54 zonal (latitudinal) confinement of the occurrence of periodic structure in TEC prior to the onset
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56 of scintillation.
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5. Conclusions:

Summarizing the results it can be concluded that most of the periodic variations of TEC before the TEC bite out observed from the stations Calcutta and Baharampore during September, 2011 and Calcutta and Farakka on March-April, 2012 are confined within a latitudinal zone of 19.00°N to 26.00°N . The source and nature of this type of periodic structures in TEC need further investigation.

Although observation of periodic structures in TEC prior to occurrence of bite-outs have been reported earlier by several co-workers, their confinement to a certain latitude swath around the northern crest of the EIA in the Indian longitude sector is a unique result reported in this paper.

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cdaac/products.html#grace respectively. The data for the two Indian IGS stations (Bangalore and Hyderabad) are downloaded from the official site of IGS <http://sopac.ucsd.edu/dataBrowser.shtml>. The authors are thankful to the Head of the Department and Dr Krishnakali Basu, Physics Department, K. N. College, Baharampore, West Bengal, India and Maharaj of Bharat Sevasram Sangha, Farakka, West Bengal, India for their help during the campaign and Dr. Tarun Kumar Panth of Space Physics Laboratory, Vikram Sarabhai Space Centre for providing the ionosonde data of Trivandrum for April 2012.

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Station	Date	PRN	Time(UT)	Subionospheric Latitude(°N)	Subionospheric Longitude(°E)	Maximum peak to peak amplitude of Periodic Structure (TECU)	Periodicity (Minutes)
CALCUTTA	Sep01,2011	12	12:00-14:00	23.91-19.66	86.21-86.04	4.58	71
	Sep15,2011	2	12:00-14:00	25.15-23.36	89.33-94.31	2.98	52
	Sep19,2011	29	12:19-15:30	27.12-20.65	84.52-87.62	1.97	53
	Sep22,2011	29	12:30-15:30	25.97-20.17	85.78-87.62	3.45	113
	Sep23,2011	25	12:00-13:30	23.13-18.86	84.66-83.16	1.94	50
	Sep24,2011	26	12:00-13:30	19.12-22.89	91.36-90.82	5.2	79
		29	12:00-15:00	28.29-22.39	84.56-87.47	2.01	57
	Sep25,2011	29	12:00-15:00	26.84-20.86	84.86-87.60	2.85	41
	Apr01,2012	7	12:00-15:00	26.39-23.09	82.28-89.11	2.77	108
		13	12:00-14:30	25.07-20.30	86.64-87.60	2.13	56
		23	12:00-14:00	23.11-18.96	88.07-88.64	1.92	75
	Apr10, 2012	13	12:00-14:00	23.82-20.01	87.29-87.59	1.88	78
	Apr17, 012	7	12:00-15:00	25.83-21.17	86.41-89.66	2.54	97
	Apr19,2012	7	12:00-15:00	25.67-20.87	86.77-89.73	2.61	97
	Apr28,2012	1	12:00-13:30	16.30-21.64	92.11-91.32	2.44	67
		7	12:00-13:20	24.82-22.79	87.99-89.24	4.72	78
		8	12:00-14:40	27.65-22.55	83.56-88.43	3.44	73
BAHARAMPORE	Sep01,2011	12	12:00-14:30	25.30-18.99	86.09-85.63	5.57	100
	Sep15,2011	2	12:00-14:30	26.5-23.26	89.2-95.96	1.56	34
	Sep23,2011	25	12:00-14:00	24.52-17.43	84.52-82.80	1.85	20
	Sep24,2011	25	11:30-14:00	25.52-17.07	84.5-82.75	5.22	80
		29	12:00-15:00	27.06-21.01	84.6-87.61	1.93	65
FARAKKA	Apr01,2012	13	12:00-14:40	27.04-21.81	86.21-87.11	1.89	88
	Apr09,2012	13	12:00-14:20	25.97-21.31	86.78-87.12	2.67	49
	Apr10,2012	13	12:00-14:30	25.85-20.19	86.83-87.13	1.48	105
	Apr19,2012	7	12:00-15:30	27.60-21.43	86.34-89.70	2.89	145
	Apr28,2012	8	12:00-15:15	29.38-23.56	83.31-88.16	3.01	111
	Apr30,2012	7	12:00-15:15	26.62-19.07	87.73-90.4	1.95	92
		8	12:00-16:00	29.11-21.20	83.94-88.41	2.83	57

TABLE: 1: List of periodic structures observed in VTEC from Calcutta, Baharampore and Farakka during the month of September 2011 and March-April 2012.

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TABLE: 2: Details of the case studies of Periodic Structure observed from Calcutta, Baharampore and Farakka on 23rd September 2011 and 19th April 2012 in SV25 and SV7 satellite link respectively.

Date	SVno	Station Name	UT	Subionospheric Latitude ($^{\circ}$ N)	Subionospheric Longitude ($^{\circ}$ E)	Spatial Extent (in Degree)	Spatial Extent (in Km)	Periodicity (minute)
23 rd September 2011	SV25	Calcutta	12:00	23.13 $^{\circ}$	84.66 $^{\circ}$			50 minutes
			12:15	22.56 $^{\circ}$	84.60 $^{\circ}$	0.57 $^{\circ}$	62.7	
						0.71 $^{\circ}$	78.1	
			12:33	21.85 $^{\circ}$	84.46 $^{\circ}$			
						0.69 $^{\circ}$	75.9	
			12:49	21.16 $^{\circ}$	84.29 $^{\circ}$			
						0.52 $^{\circ}$	57.2	
			13:00	20.64 $^{\circ}$	84.14 $^{\circ}$			
		Baharam-pore	12:24	23.61 $^{\circ}$	84.38 $^{\circ}$	0.62 $^{\circ}$	68	20 minutes
			12:39	22.99 $^{\circ}$	84.22 $^{\circ}$			
						0.59 $^{\circ}$	64.9	
			12:52	22.40 $^{\circ}$	84.05 $^{\circ}$			
						0.72 $^{\circ}$	79.2	
			13:06	21.68 $^{\circ}$	83.82 $^{\circ}$			
19 th April 2012	SV07	Calcutta	12:00	25.67 $^{\circ}$	86.77 $^{\circ}$	0.31 $^{\circ}$	34.1	97 minutes
			12:14	25.36 $^{\circ}$	87.29 $^{\circ}$			
						0.39 $^{\circ}$	42.9	
			12:31	24.97 $^{\circ}$	87.82 $^{\circ}$			
						0.97 $^{\circ}$	106.7	
			13:10	24.00 $^{\circ}$	88.67 $^{\circ}$			
						1.86 $^{\circ}$	204.6	
			14:21	22.14 $^{\circ}$	89.43 $^{\circ}$			
		Farakka	12:04	27.52 $^{\circ}$	86.49 $^{\circ}$	1.39 $^{\circ}$	152.9	145 minutes
			13:06	26.13 $^{\circ}$	88.14 $^{\circ}$			
						3.42 $^{\circ}$	376.2	
			15:04	22.71 $^{\circ}$	89.38 $^{\circ}$			

Figure caption:

Figure 1: The 20° zone of reception from three stations Calcutta, Baharampore and Farakka situated along the same meridian (88.5°E).

Figure 2(a): From top to bottom the four panels show (1) the VTEC recorded at SV25 link on September 23, 2011 from Calcutta (2) the 90 minute moving average of VTEC (3) deviation of VTEC from its 90 minute moving average and (4) variation of S_4 . The periodic structure of VTEC before the bite out is encircled on the figure and the distance between the trough and crest are also shown.

Figure 2(b): From top to bottom the four panels show (1) the VTEC recorded at SV25 link on September 23, 2011 from Baharampore (2) the 90 minute moving average of VTEC (3) deviation of VTEC from its 90 minute moving average and (4) variation of S_4 . The periodic structure of VTEC before the bite out is encircled on the figure and the distance between the trough and crest are also shown.

Figure 2(c): Wavelet Power Spectrum corresponding to the deviation of vertical TEC recorded on the SV25 link during the period of 12:00-13:00 UT on September 23, 2011 from Calcutta.

Figure 2(d): Wavelet Power Spectrum corresponding to the deviation of vertical TEC recorded on the SV25 link during the period of 12:25-13:07 UT on September 23, 2011 from Baharampore.

Figure 2(e): Plot of electron density and the corresponding height of the satellite obtained from COSMIC (C004/G21) during 18:26-19:20 LT from 10°S to 11°N over the longitude range 81°E to 91°E on September 23, 2011.

- Figure 2(f): Plot of electron density and the corresponding height of the satellite obtained from GRACE (GRC1/G28) during 16:48-17:17 LT from 8°N to 4°N over the longitude range 82°E to 90°E on September 23, 2011.
- Figure 2(g): From top to bottom the three panels represents (1) the variation of C/NOFS vertical component of ion velocity (V_z) with respect to Magnetic Local time (2) magnetic latitude of the whole track on September 23, 2011 and (3) Geographic Longitude of the whole track of C/NOFS on September 23, 2011.
- Figure 2(h): The 350–km subionospheric tracks of GPS satellites which showed periodic structure in TEC prior to bite outs observed from Calcutta during September 2011.
- Figure 2(i): The 350–km subionospheric tracks of GPS satellites which showed periodic structure in TEC prior to bite outs observed from Baharampore during September 2011.
- Figure 3(a): From top to bottom the four panels show (1) the VTEC recorded at SV7 link on April 19, 2012 from Calcutta (2) the 90 minute moving average of VTEC (3) deviation of VTEC from its 90 minute moving average and (4) variation of S_4 . The periodic structure of VTEC before the bite out is encircled on the figure and the distance between the trough and crest are also shown.
- Figure 3(b): From top to bottom the four panels show (1) the VTEC recorded at SV7 link on April 19, 2012 from Farakka (2) the 90 minute moving average of VTEC (3) deviation of VTEC from its 90 minute moving average and (4) variation of S_4 . The periodic structure of VTEC before the bite out is encircled on the figure and the distance between the trough and crest are also shown.

- Figure 3(c): Wavelet Power Spectrum corresponding to the deviation of vertical TEC recorded on the SV7 link during the period of 12:00-14:24 UT on April 19, 2012 from Calcutta.
- Figure 3(d): Wavelet Power Spectrum corresponding to the deviation of vertical TEC recorded on the SV7 link during the period of 12:08-15:06 UT on April 19, 2012 from Farakka.
- Figure 3(e): Plot of electron density and the corresponding height of the satellite obtained from COSMIC (C006/G11) during 15:36–16:33 LT from 24.85°N to 27.81°N over the longitude range 75.37°E to 87.57°E on April 19, 2012.
- Figure 3(f): Plot of electron density and the corresponding height of the satellite obtained from GRACE (GRC1/G07) during 16:55–17:31 LT from 7.45°S to 5.02°N over the longitude range 107.41°E to 117.36°E on April 19, 2012.
- Figure 3(g): From top to bottom the four panels represents the data recorded by ionosonde installed at Trivandrum on April 19, 2012 where (1) the calculated N_mF_2 variation with respected to UT (2) h_mF_2 variation with UT (3) $h'F_2$ variation with UT and (4) f_0F_2 variation with UT.
- Figure 3(h): The 350–km subionospheric tracks of GPS satellites which showed periodic structure in TEC prior to bite outs observed from Calcutta during March-April 2012.
- Figure 3(i): The 350–km subionospheric tracks of GPS satellites which showed periodic structure in TEC prior to bite outs observed from Farakka during March-April 2012.

Figure 1

Figure: 1

Figure 2(a)

Figure 2(a)

Figure 2(b)

Figure: 2(b)

Figure 2(c) BW

Figure : 2(c)

Figure 2(c) colour

Figure : 2(c) Coloured

Figure 2(d) BW

Figure : 2(d)

Figure 2(d) Colour

Figure : 2(d)Coloured

Figure 2(e)

Figure: 2(e)

Figure 2(f)

Figure: 2(f)

Figure 2(g)

Figure: 2(g)

Figure 2(h)

Figure: 2(h)

Figure 2(i)

Figure: 2(i)

Figure 3(a)

Figure: 3(a)

Figure 3(b)

Figure: 3(b)

Figure 3(c) BW

Figure: 3(c)

Figure 3(c) colour

Figure: 3(c) coloured

Figure 3(d) BW

Figure: 3(d)

Figure 3(d) Colour

Wavelet Power Spectrum for April19, 2012
Station: Farakka, SV7, Time Duration: 12:08-15:06 UT

Figure: 3(d) coloured

Figure 3(e)

Figure: 3(e)

Figure 3(f)

Figure : 3(f)

Figure 3(g)

Figure: 3(g)

Figure 3(h)

Figure: 3(h)

Figure 3(i)

Figure: 3(i)