Impact of equatorial ionospheric irregularities on transionospheric satellite links observed from a low-latitude station during the minima of solar cycle 24

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Effects of equatorial ionization density irregularities on transionospheric communication and navigation links have been studied during the abnormally prolonged minima of the 24th solar cycle from Calcutta, a station situated virtually underneath the northern crest of the equatorial ionization anomaly in the Indian longitude sector. Scintillations at L-band have been sparse during 2008-2010 with four cases of GPS scintillations being observed from Calcutta. It is interesting to note that all these cases of scintillations were observed when the irregularities were field-aligned. One of the cases occurred on 25 September 2008 when GPS SV12 link exhibited depletions in TEC of nearly 8 TEC units around 15:30 hrs UTC associated with fluctuations in carrier-to-noise (CNO) ratio at L1 frequency and position dilution of precision (PDOP). The 1-min $S_4$ index reached a maximum value of 0.48 [SI=11dB] on the SV12 link around 15:30 hrs UT. The geostationary FLEETSATCOM link at 250 MHz was also disrupted during the period 15:55-16:25 hrs UT with maximum $S_4$ of 0.69 [SI=17dB]. The ambient ionization and strength of the equatorial electrojet was higher on that day than other days around that period. The F-region height rise around sunset was significant as indicated by a flat-topped ionization density distribution over the magnetic equator by Defense Meteorological Satellite Program (DMSP).

Keywords: Equatorial ionospheric irregularities, Transionospheric communication, Carrier-to-noise (CNO) ratio, Position dilution of precision (PDOP), Equatorial electrojet (EEJ) strength, Slant total electron content (STEC)

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1 Introduction

Equatorial ionospheric irregularities remain an enigma for transionospheric satellite link users even after more than six decades of extensive research. Excellent review articles on equatorial ionospheric F-region irregularities are available1. Scattering of signals from these irregularities embedded in the ionosphere are obtained in the form of spread-F on radar maps1,2. Plasma depletions were first observed by the polar orbiting OGO-6 satellite3. The irregularities, in the form of depletions, manifest as deep bite-outs in in situ density plots4,5 and cause scintillations in transionospheric satellite links6,7. Kil & Heelis8 have reported the global distribution of ionospheric irregularities from the Atmospheric Explorer-E (AE-E) satellite data. Airglow observations with all-sky cameras establish that the irregularity clouds become narrower with latitude on both sides of the magnetic equator9. Both airglow observations and scintillations with orbiting satellites show that the irregularity clouds may split into several streams as one moves away from the equator10.

The term space weather refers to conditions on the sun and in the solar wind, magnetosphere, ionosphere and thermosphere that can influence the performance and reliability of space and ground-based technological systems and can endanger human life or health. The effects of severe space weather events constitute one of the most intense propagation phenomena affecting satellite-earth station links, often causing complete outages of signals for prolonged periods of time, thereby, jeopardizing human lives in the modern space-based society. In the equatorial region, these events are mainly concentrated within a geomagnetic latitude extent of ±20°. The equatorial ionosphere is characterized by the equatorial ionization anomaly (EIA) over a major part of the day and ionospheric F-region irregularities causing amplitude and phase scintillations on transionospheric satellite links during the post-sunset period.

Global Positioning System (GPS) satellite signals travelling from the satellite to the Earth are subject to a variety of error sources, the most significant among them being multipath and the effects of the
ionosphere. Of the ionospheric contributions, the background ionosphere introduces both delay and frequency dispersion whereas small-scale time-varying irregularities introduce phase and amplitude scintillations of the received signal. The issue of serious concern to transionospheric satellite link users in the equatorial region stems from the fact that these cases of intense amplitude and phase scintillations occur in this region even under very low sunspot number and magnetically quiet conditions.

Near the northern crest of the EIA in the early evening hours, intense to saturated scintillations with a very fast fading rate are noted on VHF satellite links caused by irregularities of scale sizes 800-1000 m. At this time, smaller scale irregularities of scale sizes 300-400 m are also present and may cause scintillations on geostationary L-band as well as GPS links mainly concentrated around the northern crest of the EIA. With the progress of the night, as the smaller scale irregularities gradually decay but the larger scale irregularities still persist, geostationary L-band scintillations die down but VHF links are still affected. However, around this time, GPS links looking south from the northern crest of the EIA ‘end-on’ through an irregularity which exists in the form of a ‘peeled banana’ section experience scintillations. Detailed theoretical understanding of observation of pronounced scintillations around the region of field-alignment are reported\(^{11,12}\).

The condition of field-alignment cannot be observed with a geostationary satellite from a station situated in the equatorial region. For observations with GPS from an off-equatorial station like Calcutta, there would thus be two regions of enhanced scintillations: i) one around the crest of the EIA due to a high ambient ionization\(^{13}\), and ii) the other in the direction looking towards the magnetic equator\(^{14,15}\). The second case is peculiar to stations near the crest of the anomaly around local midnight when VHF scintillations are recorded on a geostationary satellite link with no scintillations at L-band.

Geostationary VHF satellite beacon from FLEETSATCOM (FSC – 250 MHz; 73°E) has been routinely recorded at the Institute of Radio Physics and Electronics (IRPE), University of Calcutta, Calcutta, India (22.58°N, 88.38°E geographic; magnetic dip 32°N) since 1980. A dual-frequency software-based high resolution GPS receiver capable of providing the raw phase of the GPS L1 (1575.42 MHz) and L2 (1227.6 MHz) signals is operational at IRPE. IRPE is also part of the international SCIntillation Network Decision Aid (SCINDA) program of the US Air Force where a dual-frequency ionospheric TEC and scintillation monitor operates round-the-clock since November 2006. This station, being situated virtually under the northern crest of the EIA in the Indian longitude sector, has a unique advantage of studying the equatorial ionospheric irregularities.

The daytime equatorial electrojet (EEJ) controls the development of the equatorial anomaly\(^ {16}\) and it has been suggested that a developed equatorial ionization anomaly in the daytime plays a crucial role in the subsequent development of F-region irregularities in the post-sunset hours\(^ {17}\). However, no idea about the pre-reversal enhancement of the ExB drift in the post-sunset hours can be obtained from magnetogram records since the electrojet current, which is conducting in nature, disappears in that local time interval. The enhanced electric field is attributed to the polarization effect due to the F-region dynamo\(^ {18}\). The coupling between the E and F-layers around the solar terminator has been explained as a spillover of the dayside equatorial electrojet into the F-layer\(^ {19,20}\), which causes the low latitude plasma to rise.

In the equatorial latitudes around sunset, an enhancement of the eastward electric field occurs commonly referred to as pre-reversal enhancement (PRE). This enhanced electric field raises the electron density to the topside and reverses the process of normal decay of the EIA. Sometimes, the post-sunset anomaly becomes more developed than the daytime phenomenon. The EIA is not confined to the maximum ionization height, \(h_{mF2}\), but extends up to several hundred kilometers in the topside of the ionosphere. The locus of the ionization crests in the topside lies on a field-line. A larger post-sunset enhancement of the eastward electric field may raise the apex of the equatorial ionization anomaly over the magnetic equator to heights above the nominal altitude of satellites like DMSP (840 km). As the satellite moves across the equator, the ionization density would then either show a flat top or two crests at off-equatorial latitudes. It has been suggested that an idea about the occurrence of post-sunset scintillations may be obtained from the latitudinal distribution of ion density by DMSP in the afternoon hours\(^ {21-23}\).

On days when the pre-reversal enhancement of the eastward electric field forces the apex of the
equatorial anomaly to rise to heights of 750 km or higher over the magnetic equator, the irregularities map to off-equatorial latitudes like Calcutta (22.58°N geographic latitude) along the magnetic field lines in the post-sunset hours. The magnetic field line with the apex at 840 km above the magnetic equator maps to 18°N magnetic latitude (23.8°N geographic latitude) at the mean ionospheric height of 350 km. Thus, a strong association may be expected between the latitudinal variation of the ion density over the magnetic equator and occurrence of scintillations near the northern crest of the equatorial anomaly at Calcutta21-23. Locations near the anomaly crests experience worst-case disruptions in satellite based communication and navigation links and provide ideal test bed to check the reliability of operation of such services.

In the equatorial latitudes, isolated cases of occurrences of post-sunset ionospheric scintillations affecting GPS links have been recorded during the unusually prolonged minimum of solar cycle 24 in 2008-2010 even under magnetic quiet conditions. These events of scintillations, observed on both the amplitude and phase of the GPS signals, were found to cause tracking jitters on GPS receivers leading to cycle slips or phase lock loss. The associated bite-outs in the total electron content (TEC) were significant and resulted in abnormally high range errors leading to a considerable compromise on the accuracy of position-fixing. The extremely sharp gradients of ionization existing on the walls of the TEC bite-outs may jeopardize the reliability of operation of satellite links operating through such regions. This paper presents a case study of an event which occurred on 25 September 2008 as a representative case.

2 Data

Occurrences of scintillations at L-band have been extremely sparse during the abnormally low solar activity period of 2008 through March 2010 as observed from Calcutta (22.58°N, 88.38°E geographic; magnetic dip 32°N), a station lying near the northern crest of the equatorial ionization anomaly. Only four cases have been recorded during 2008 - March 2010, namely, on 2 February 2008, 25 September 2008, 8 October 2009 and 13 March 2010, when amplitude and phase scintillations were observed on GPS L1 frequency (1575.42 MHz) with associated deep bite-outs in TEC and fluctuations in carrier-to-noise (CNO) ratios at GPS L1 frequency.

The present paper highlights the event which occurred on 25 September 2008 for understanding the characteristics of these intense space weather events occurring in the equatorial region even during the bottom of the solar minima under magnetically quiet conditions. A detailed discussion on the space weather events of 8 October 2009 and 13 March 2010 is available in literature24.

Amplitude of the VHF carrier signal (244.156 MHz) from FLEETSATCOM (FSC) (350 km subionospheric point: 21.10°N, 87.25°E geographic; magnetic dip 28.65°N) has been regularly recorded at Calcutta since 1980 using a wideband communication receiver. The receiver is calibrated once a week using a HP Signal Generator (HP8648C model) following Basu & Basu25. The dynamic range of the receiver is −25 dB. The scintillation data has been scaled to obtain scintillation index [SI, dB] following Whitney et al.25 and the corresponding S4 using Whitney26.

The data recorded by the dual-frequency ionospheric TEC and Scintillation Monitor at Calcutta under the SCINDA program are sampled at 1 s and continuously uploaded to the website http://capricorn.bc.edu/scinda/india from where they are available in a post-processed form to authorized users. Plots of S4 and elevation angles from GPS satellite vehicles as a function of Zulu time (LT = UT + 06:00) hrs, polar plots of GPS S4 indicating the intensities of amplitude scintillations along the tracks using different shades and diurnal variation of calibrated TEC from different satellite vehicles are available from the SCINDA website. The carrier-to-noise ratio (CNO) of the L1 signal, slant TEC (STEC) and 1-min S4 index are utilized from this receiver.

From the dual-frequency software-based GPS receiver, position dilution of precision (PDOP) factor has been utilized at different elevation angles and local times on the day of the above mentioned space weather event. To avoid any multipath effects, GPS data above an elevation angle of 15° only have been used for all analysis.

The time available from the GPS receivers are in Universal Time Coordinated (UTC). UTC is comprised of inputs from a time scale derived from atomic clocks and a time scale referenced to the Earth’s rotation rate. GPS system time is referenced to UTC. GPS disseminates a form of UTC that provides the capability for time synchronization of users worldwide.
The strength of the electrojet could be measured by the differences between the hourly inequalities ($\Delta H$) of the horizontal component (H) of the geomagnetic field at a station near the magnetic equator, situated close to the axis of the EEJ, and another station located away from the magnetic equator, outside the electrojet region. This eliminates any non-ionospheric contribution to the magnetic field variation, e.g. magnetospheric contributions. In the Indian subcontinent, geomagnetic data from Tirunelveli (latitude 8.67°N, longitude 77.82°E geographic; magnetic dip 0.5°N) situated within the EEJ and Alibag (latitude 19.00°N, longitude 72.83°E geographic; magnetic dip 24.75°N) outside the EEJ have been used to obtain an estimate of the strength of the EEJ. Denoting the hourly inequality of the horizontal component of the geomagnetic field at Tirunelveli by $\Delta H_T$ and that at Alibag by $\Delta H_A$, a measure of the electrojet is given by $\Delta(H_T - H_A)$ (Refs 16,26).

Distribution of topside ionization density during the days of the intense space weather events as well as on days preceding and following them have been obtained using DMSP ion density data recorded with a resolution of 4 s, made available from the US Air Force Research Laboratory. The hourly Dst indices have been obtained from the website of the World Data Centre for Geomagnetism, Kyoto (http://wdc.kugi.kyoto-u.ac.jp).

3 Results

Figure 1 shows a map of India with the position of Calcutta and the 350-km subionospheric point of FSC indicated. The stations at Tirunelveli near the magnetic equator and Alibag situated outside the EEJ belt are marked; magnetic equator and northern crest of the EIA in the Indian longitude sector are also shown.)
magnetic equator and Alibag situated outside the EEJ belt are marked in the figure. The magnetic equator and the northern crest of the EIA in the Indian longitude sector are also shown in this figure.

Figure 2 shows the plot of $S_4$ and elevation angle of different GPS satellites recorded by the SCINDA receiver from Calcutta on 25 September 2008. It may be noted from Fig. 2 that the frame corresponding to SV12, enclosed by a red border, shows fluctuations in $S_4$ around 15:30 hrs UTC with maximum value of nearly 0.5. A plot showing the 350-km subionospheric track of SV12 and geostationary FSC is shown in Fig. 3 along with the location of the station Calcutta. The portions of the track marked in red correspond to periods of $S_4 \geq 0.15$ during 15:04-15:06 hrs UTC and again during 15:15-15:37 hrs UTC. During the interval 15:04-15:06 hrs UTC, $S_4$ varied over a range 0.15-0.18. In the second patch observed during 15:15-15:37 hrs UTC, the corresponding variations of $S_4$ were from 0.15 at 15:15 hrs UTC to a maximum of 0.48 [SI=11 dB] at 15:28 hrs UTC and finally down to 0.22 at 15:37 hrs UTC. During the time interval 15:04-15:37 hrs UTC, the satellite moved predominantly in north to south direction. The 350-km subionospheric latitude of the satellite varied from 19.60°N to 17.50°N while the corresponding subionospheric longitude ranged from 86.34°E to 86.24°E. During this time, the satellite was located south of Calcutta having elevation in the range 38.73°-26.29° and azimuth lying in the range 213.08°-202.09°.
The vertical panels of Fig. 4(a) show the elevation, moving averaged deviation of CNO at GPS L1 frequency (CNO-L1), slant TEC (STEC), $S_4$ index and moving averaged deviation of PDOP corresponding to SV12 for 25 September 2008. Fluctuations in CNO-L1 are noted during 15:00-16:00 hrs UTC with maximum around 15:30 hrs UTC. This is closely associated with bite-outs in TEC around 15:30 hrs UTC enclosed within arrows, maximum of $S_4$ and sharp fluctuations in PDOP. On 25 September 2008, the maximum depletion in TEC from the ambient level was 8 TEC units (1 TEC unit = $1 \times 10^{16}$ electrons m$^{-2}$) with corresponding maximum CNO fluctuation of 4 dB-Hz on the SV12 link. The deviation of PDOP was found to vary from -8 to 2 during 15:00-16:00 hrs UTC. Variations of hourly Dst indices for September 2008 are plotted in Fig. 4(b). It is noted that the variations of the Dst index during 23-27 September 2008 ranged from -9nT to +12nT.

Figure 5 shows the variation of STEC on the SV12 link on individual days of the period 23-27 September 2008. The average, during this period along with the $\pm 1\sigma$ level, is also plotted in this figure. The afternoon ionization on the day of occurrence of scintillations was perceptibly higher than the average value, much above the $+1\sigma$ level.

The carrier amplitude of the 250 MHz beacon from the geostationary FSC recorded at Calcutta during 15:50-16:50 hrs UT has been shown in the top panel of Fig. 6. The bottom panel of Fig. 6 shows the 1-min $S_4$ index corresponding to patches of amplitude scintillations [$S_4 \geq 0.175$, SI $\geq 3$ dB] observed on the geostationary FSC link from Calcutta. Patches of amplitude scintillations are noted starting from 15:57 hrs UT which continued till 16:24 hrs UT. VHF amplitude scintillations were intense [$S_4 \geq 0.45$; SI $\geq 10$ dB] particularly during 16:00-16:21 hrs UT when $S_4$ values reached a maximum of 0.69 [SI=17 dB].

The development of the EIA is mainly controlled by the EEJ. Under strong electrojet conditions, the anomaly is developed in the afternoon hours with a
The shallow gradient of the F-region ionization in the region between the crest and the trough. Diurnal plot of the strength of the EEJ given by $\Delta(H_T - H_A)$ for 23-27 September 2008 is shown in Fig. 7. It may be noted that the diurnal maximum value of EEJ was higher on 25 September 2008 (73 nT) compared to the other days.

The different panels of Fig. 8 show ion densities measured by DMSP F15 on 25 September 2008 over a magnetic latitude range of $\pm 70^\circ$ in different longitude sectors around the globe. It is extremely interesting to note that only in the panel enclosed by the red lines with equator crossing longitudes of 88°E at 12:47 hrs UT, which correspond to local afternoon/early evening hours in the Indian longitude sector, flat-topped ionization density distributions...
Fig. 7 — Diurnal plots of the strength of the EEJ for 23-27 September 2008

Fig. 8 — Different panels show ion densities measured by DMSP F15 on 25 September 2008 over a magnetic latitude range of ±70° in different longitude sectors around the globe; Panel enclosed by a red line corresponds to 88°E and 12:47 hrs UT.
have been recorded. This is indicative of the fact that the F-region apex height exceeded the nominal 840 km altitude of DMSP satellites on 25 September 2008.

4 Discussions

The abnormally prolonged solar minimum of the 24th solar cycle presented unique opportunities for studying the background equatorial ionization processes affecting transionospheric communication and navigation links. Scintillation observations at L-band were very rare during the period 2008-2010 and the GPS links observed from Calcutta were affected on very few occasions. However, it was very interesting to note that majority of these cases occurred under a special propagation condition when the ray makes a small angle with the field-line. These results put forward the suggestion that intense amplitude and phase scintillations and associated deep bite-outs in TEC may affect transionospheric satellite links in the equatorial region even under magnetically quiet conditions at the bottom of the solar cycle. Thus, SBAS system designers operating in the equatorial region have to make a very careful analysis of propagation geometry related scintillation phenomena using a wide network of reference stations. Near the bottom of the solar cycle, the ambient ionization is low and the overall strength of the irregularities, if any, would also be low. Thus, under this special propagation condition, even the weak field-aligned irregularities found in the late evening hours may produce large phase perturbations and enhanced amplitude scintillations.

An examination of the geometry of propagation indicates that GPS satellite signals often exhibit scintillations when the ray path becomes highly field-aligned and the propagation angle attains a value of about 172.70°. The propagation angle calculated using IGRF-11 (2010) magnetic field model show that GPS satellites observed from Calcutta achieve a near ‘end-on’ propagation with propagation angle in the range of 171.41°-169.94° at 15.03°-28.02° elevation around 179.89°-185.26° azimuth from the station corresponding to 350-km subionospheric points 13.90°-17.44°N, 88.35°-87.86°E geographic; 16.01°-23.17°N magnetic dip. Thus, the ionospheric pierce point of SV12 was close to the zone of maximum propagation angle during the time interval 15:04-15:37 hrs UTC when the satellite link exhibited scintillations with $S_4 \geq 0.15$.

The event highlighted in the present paper, which occurred on 25 September 2008 resulted in maximum $S_4$ index of 0.48 and bite-out on slant TEC of 8 TEC units on the GPS SV12 link as observed from Calcutta. It is important to note that the corresponding range error at GPS L1 frequency is 1.44 m. The sharp fluctuations in PDOP coincident with high values of $S_4$ and bite-outs on slant TEC imply degradation of positional accuracy even under unusual low solar activity conditions. Occurrence of intense bite-outs of ion density (maximum relative irregularity amplitude $\Delta N/N \sim 65\%$) were detected earlier on 29 October 1994 using in situ measurements by SROSS-C2 coupled with deep fading ($S_4 \sim 1$ at VHF, $\sim 0.52$ at L-band, and $\sim 0.69$ at GPS L1 frequency) on ground-based satellite links from Calcutta. Degradation of navigational accuracy of GPS during periods of scintillations under the low sunspot number period of 1995 has previously been reported from Calcutta. A study of scintillations at 40 and 41 MHz from BE-B and BE-C satellites recorded at Ahmedabad (latitude 23.06°N, longitude 72.61°E geographic; 33.95°N magnetic dip) during the years 1964-68 is available in literature. It may be noted that Calcutta, being situated virtually underneath the northern crest of the EIA, records very high values of TEC. No dual-frequency GPS TEC data are available from Calcutta for the 23rd solar maximum in 2000-2001. Long-term records of vertical TEC recorded at Calcutta during 1977-1990 using geostationary ETS-2 shows values $\sim 80-95$ TEC units during 12:00-15:00 hrs UT on different days of April 1989. This may translate to slant TEC values in excess of 160 TEC units.

The irregularity cloud, comprising of different scale sizes, may be tracked both in space as well as in time using GPS as shown in Fig. 3. The track of SV12 was predominantly in north-south direction during 15:04-15:37 hrs UTC when the 350-km subionospheric longitude of the satellite varied in the range 86.34°-86.24°E. Hence, this will not affect the west-east drift velocity of the irregularity. CNO fluctuations on SV12 commenced from 15:07 hrs UTC while carrier amplitude fluctuations were noted on geostationary FSC from 15:45 hrs UTC. The leading edge (eastern wall) of the cloud crossed the satellite link at 15:37 hrs UTC causing the bite-out on slant TEC. The trailing edge (western wall) of the cloud crossed the satellite link at 15:37 hrs UTC resulting in restoration of TEC to its ambient level. Thus, an idea about the extent of the bubble may be obtained assuming a
nominal eastward drift velocity of 150 m s\(^{-1}\) during 15:00-16:00 hrs UTC. Presence of significant eastward or westward velocity of the satellite vehicle at the ionospheric height would have resulted in increased or reduced times of observation of the effects of the irregularity. As the difference in the 350-km subionospheric longitudes of GPS SV12 during 15:04-15:37 hrs UTC and geostationary FSC was 0.95° (86.3°E and 87.25°E, respectively), this amounts to a separation of ~105 km at subionospheric heights in the equatorial region. Thus, it may reasonably be assumed that the same irregularity cloud affected both GPS SV12 and geostationary FSC link.

It is interesting to note that the ambient ionization, which is understood to be one of the background conditions conducive for the generation of irregularities, was significantly higher on 25 September 2008 in comparison to other days during the period 23-27 September 2008. The magnitude of amplitude scintillations being proportional to the electron density along the ray path of the radio wave between the satellite and the receiver, a relatively high ambient ionization may be treated as an important factor for the occurrence of scintillations.

The high value of EEJ on 25 September 2008 in comparison to other days over the period 23-27 September 2008 provides validation of the suggestion that under strong electrojet conditions, the EIA is developed in the afternoon hours with a steep gradient of the F-region ionization in the region between the crest and the trough\(^{18}\). A developed equatorial anomaly in the afternoon hours may be taken as a precursor to equatorial spread-F or scintillations on trans ionospheric links\(^{17,22}\). The rise of the apex of the F-layer to heights in excess of 700-800 km over the magnetic equator was corroborated by DMSP ion density measurements at 840 km by showing flat-topped ionization distribution over the Indian longitude sector.

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