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Characteristics of Equatorial F-region Irregularities along the 90ºE Meridian during High Solar Activity Phase

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Abstract

This study investigated the characteristics of the Equatorial ionospheric F-region Irregularities (EFIs) along the 90ºE meridian using the phase fluctuations of Global Navigational Satellite System (GNSS) signals during the maximum phase of solar activity in the solar cycle 24. Results indicate that the occurrence of EFIs is related to the local time, season and magnetic latitude. The EFIs are usually observed during the post-sunset hours and are more pronounced before midnight. In the equinox seasons, EFIs are more common and intense around the magnetic equator and low latitude regions. The disappearance time of EFIs is late during the spring equinox season than the autumn equinox. The occurrence probability of severe EFIs is high in the equinox seasons than in the solstice seasons, especially in spring equinox. Moderate EFIs are observed more in the spring equinox season over the pole-ward edge of the Equatorial Ionization Anomaly (EIA) region in both the hemispheres. This study helps in understanding the spatio-temporal characteristics of EFIs and thereby mitigating the scintillation effects in highly precise and dynamic applications of satellite-based navigation systems over the equatorial and low latitude Indian sector.

1. Introduction

Electron density irregularities in the ionosphere is one of the known space weather effects which is a major concern for radio science community today due to its significant impact on satellite radio communication. Trans-ionospheric signals such as the Global Navigation Satellite System (GNSS) signals may experience scintillations in their phase and amplitude due to the movement of irregularities across the signal path, with a resultant impact on the overall performance of the system. The characteristics of the ionospheric irregularities, specifically its electron density distribution, fluctuates with time, location, season and solar activity. Ionosphere irregularities mostly occur after sunset and are more frequent and intense in latitudes near the magnetic equator and auroral zone though the formation mechanism is different for both the sectors [1], [2]. Equatorial F-region Irregularities (EFIs) has been connected to the dusk time enhancement of eastward electric fields, known as the pre-reversal enhancement (PRE) effect. The PRE leads to an unstable condition in the plasma structuring at the bottom side of F-layer for developing Equatorial Plasma Bubbles (EPBs) which can be explained through the Rayleigh-Taylor (R-T) instability. The zonal and meridional drifting characteristics of plasma bubbles refer to the movement of EFIs in the East-West or North-South direction. The EFIs can be observed by using GNSS phase fluctuations associated with the frequency-dependent dispersive characteristic in the ionosphere, by computing the rate of change of Total Electron Content (TEC) index (ROTI) along the ray path length. Several studies are carried out over the Indian region to characterize the seasonal and solar cycle variations of EFIs using ground-based ionosonde, GNSS, radar and other space-based observations [3]–[5]. Vankadara et al. [6] have found the signatures of ionospheric irregularities and their pole-ward shifting characteristics over Indian longitudes during a severe space weather condition from the ROTI observations at a latitudinal chain of GNSS stations.

The current study investigates the diurnal localtime, season and latitudinal distribution of EFI occurrence using GNSS-derived ROTI observations along the 90ºE meridian in the Indian longitude sector during the high solar activity year (2014) of the solar cycle 24.

2. Methodology:

The present study analyses observables from four GNSS stations, latitudinally aligned from -10 to 29ºN in the eastern side of Indian region during the year 2014 (Table 1). The stations are selected around 90ºE meridian to analyze the longitudinal variations of the irregularities. Dual frequency Global Positioning System (GPS) phase (Φ1 and Φ2) and pseudorange (P1 and P2) observables recorded at the ground-based stations are used to derive the TEC across the signal path. The rate of change of TEC Index (ROTI) is then computed from the TEC at each location to detect the plasma irregularities [7]. ROTI can be considered as a low-resolution proxy to scintillation index (S4), which can be determined from the standard deviation of Rate of change of TEC (ROT) as per Equation 1.

$$ROT = \frac{VTEC_n^i - VTEC_{n-1}^i}{(t_n - t_{n-1})} \quad (1)$$

Here i denotes the visible PRNs and t indicates epoch times. Hence, $t_n - t_{n-1}$ represents the epoch intervals.

The ROTI for each PRN is determined by computing the 5-min standard deviation of ROT as given in Equation 1.

$$ROTI = \sqrt{\langle ROT^2 \rangle - \langle ROT \rangle^2} \quad (2)$$

Where ⟨ ⟩ refers to averaging the values over every 5-min interval.

In order to minimize the multipath and other lower atmospheric effects, an elevation angle of 30 degrees is chosen in this study. Also, the days with geomagnetic Kp index below 2 are used for the analysis to understand the variations of EFIs in the magnetically quiet period. Based on the magnitude of ROTI, the irregularities are levelled into three categories, namely ROTI less than 0.4 (no irregularities), ROTI from 0.4 to 0.8 (moderate irregularities) and ROTI more than 0.8 (strong irregularities) following the classification scheme adopted by Adebiyi et al [8] over the African low latitude sector.
The monthly, seasonal and hemispheric asymmetry of EFIs are studied by using monthly mean ROTI across the 90ºE meridian during the year 2014, the maximum solar activity period under solar cycle 24 (Figure 1). Further, the seasonal occurrence probability of each category of irregularities (moderate and severe) is examined at all the stations as shown in Figure 2.

Table 1. Geographic and geomagnetic coordinates of GNSS stations in both hemispheres considered in this study.

S. No.	Station Name/ Code	Geo. Lat. (ºN)	Geo. Lon. (ºE)	Mag. Lat. (ºN)	Mag. Lon. (ºE)
1.	Cocos (COCO)	-12.18	96.83	-21.68	168.80
2.	Port Blair (PBR2)	11.64	92.71	2.13	165.74
3.	Khulna (KHL2)	22.80	89.53	13.37	163.02
4.	Lhasa (LHAZ)	29.66	91.10	20.11	164.86

3. Results and Discussion

3.1 Monthly average variations of EFIs

The contour plots of monthly diurnal average ROTI for the year 2014 at all the four stations (Figure 1) indicates distinct local time and latitude dependence on the occurrence of irregularities. The high value of ROTI is typically observed between 13:00 UT (18:30 LT) to 19:30 UT (01:00 LT) with maxima around 15:00 UT (20:30 LT) for a station near the magnetic equator (PBR2) and low latitude EIA region station (KHL2). It is due to the existence of eastward electric fields in the post-sunset hours and robust plasma density gradient between the upper and bottomside of the ionosphere F layer [9]. Also, the timing of disappearance of EFIs varies with season and latitude. At KHL2, the EFIs disappear early compared to the equatorial location (PBR2). Likewise, the magnitude and time of disappearance of EFIs are more in spring equinox months compared to the autumn equinox months for both the stations PBR2 and KHL2. This confirms significant equinoctial asymmetries in terms of frequency of occurrence of the EFIs [10]. The ROTI values from the stations COCO and LHAZ with almost same magnetic latitudes in south and north hemisphere are relatively small compared to the PBR2 and KHL2 locations. This could be due to the large density gradient in local ionosphere around the magnetic equator and low latitude EIA region. However, the ROTI values are high at COCO compared to LHAZ, indicating the hemispheric asymmetry of the occurrence of EFIs at the conjugate locations. Hence, it is clear that EFIs occurrences are more prominent in the southern hemisphere compared to the northern hemisphere [8].

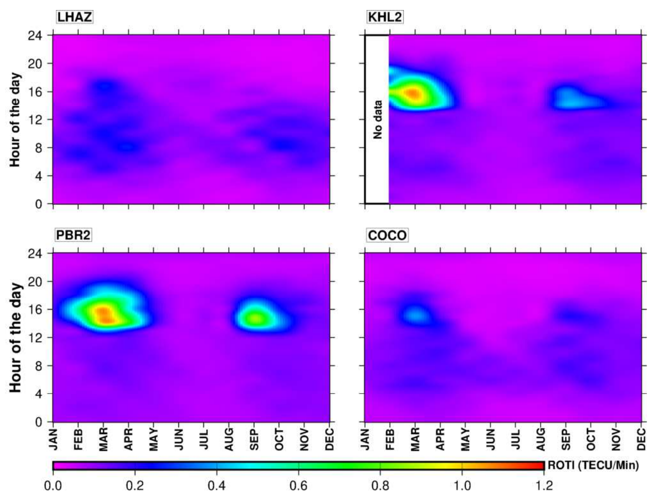

Figure 1. Monthly diurnal average ROTI for the stations COCO, PBR2, KHL2, and LHAZ during the year 2014.

3.2 Seasonal occurrence probability of severe and moderate EFIs

The seasonal occurrence probability of severe and moderate EFIs at all stations is calculated and plotted in Figure 2. It can be observed from the results that the severe irregularities are mostly observed at the station (PBR2) close to the magnetic equator and low latitude EIA location (KHL2). The percentage of occurrence of severe EFIs is more in the equinox seasons compared to solstice seasons. These findings are consistent with the previous studies conducted in the other regions which report more frequent and severe EFIs observed in the equinox seasons [11], [12]. Also, the frequency of occurrence of severe EFIs is high in the spring equinox compared to the autumn equinox (Figure 1). For PBR2 and KHL2, the occurrence rate of moderate EFIs is high in the winter solstice compared to summer solstice due to the winter anomaly characteristics of the ionosphere, corresponding to the global thermospheric circulation from summer to winter hemisphere. The Percentage of occurrence of severe EFIs is low at COCO and LHAZ as their magnetic latitudes lie on the pole-ward edge of EIA region in both hemispheres. The maximum occurrence rate of moderate EFIs is observed in the pole-ward edge of the EIA region in both the hemispheres (COCO and LHAZ) in spring equinox season which disappears in summer solstice.

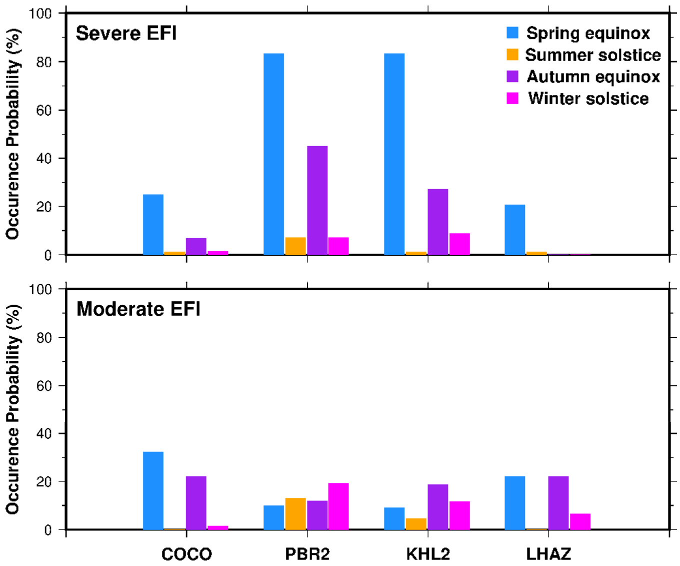

Figure 2. Seasonal occurrence probability of severe and moderate EFIs for COCO, PBR2, KHL2, and LHAZ during the year 2014.

4. Conclusion

We investigated the variations of Equatorial F-region Irregularities (EFIs) across 90°E meridian during the high solar activity year (2014) of 24th solar cycle using a longitudinal chain of four GNSS observatories. The local diurnal, seasonal and longitudinal characteristics of plasma irregularities are demonstrated through a relatively low-resolution ROTI variable extracted from GPS data of these four stations. Significant insights on EFIs from this study are listed below:

i. The occurrences of EFIs are dependent on the local time and magnetic latitude and are typically observed in the post-sunset hours and are more pronounced during pre-midnight hours.

ii. The occurrences of EFIs are more frequent and intense in the latitudes near magnetic equator and low latitude regions in the equinox seasons, particularly in spring equinox.

iii. The time of the disappearance of EFIs is late during the spring equinox season compared to the autumn equinox.

iv. The occurrence probability of severe EFIs is high in the equinox seasons as compared to the solstice seasons around the magnetic equator and low latitude EIA region.

v. The occurrence probability of moderate EFIs is high in the spring equinox season over the pole-ward edge of the EIA region.

The results from this research work would add to the efforts for mitigating the effects of EFIs in highly precise and dynamic applications relying on space-based navigation systems, particularly over the equatorial and low latitude Indian longitude sector. Further, the study aims at extending the analysis to other longitudes with a dense network of geodetic GNSS stations across the Indian region.

5. Acknowledgments

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