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Spectral properties of sub-kilometer-scale equatorial irregularities as seen by the Swarm satellites

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Abstract

The faceplates on-board the Swarm satellites have provided high-resolution measurements of electron density at a frequency of 16 Hz along the satellite paths. The 16-Hz electron density data from Swarm were analyzed to determine the spectral characteristics of the F-region ionospheric irregularities at Swarm altitudes. The electron density data covered all geographic longitudes with quasi-dipole latitude limited between $\pm 30^\circ$ and the period considered was from October 2014 to October 2018, when the data was available. The Power Spectral Densities (PSDs) observed follows a power law. The values of spectral indices obtained showed a peak centered at around -2.5 , located at the Equatorial Ionization Anomaly (EIA) belts. The spectral indices were found to be sensitive to irregularity amplitude. The local time distribution of the spectral indices also showed a peak within the time sector 20:00 LT - 22:00 LT and then decreased gradually after about 22:00 LT till 06:00 LT. The peak of the spectral index was also observed in the South American-Atlantic-African longitudes and it was generally low in the Asian-Pacific region. The angle between the Swarm satellite orbital path and the magnetic field ($\chi(B, v)$) was also examined and it was observed that the highest percentage of occurrence of ionospheric irregularities and the peak in spectral index was obtained only when the $\chi(B, v)$ was between 20° and 40° . The local turbulence is anisotropic with respect to the background magnetic field as indicated by a more negative spectral index for larger $\chi(B, v)$.

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Keywords: Ionospheric irregularities; Power Spectral Density (PSD); Spectral index

1. Introduction

The equatorial ionosphere is highly dynamic and is characterised by the existence of ionospheric irregularities which occur after sunset in the F region (Kil and Heelis, 1998). They have been observed as electron density drop-outs along satellite passes referred to as equatorial plasma bubbles (EPBs) or range and frequency spread signatures on ionograms called equatorial spread F (ESF)

(Woodman and La Hoz, 2012; Burke et al., 2004). The Rayleigh–Taylor instability (RTI) is the suggested mechanism which can explain how ionospheric irregularities occur in the low latitudes (Woodman and La Hoz, 2012; Schunk and Nagy, 2009; Kelley, 2009). The occurrence of ionospheric irregularities has been of high scientific interest because they affect radio signals traversing through the ionosphere (Yeh and Liu, 1982; Aarons, 1982; Kintner et al., 2007). The scale size of these irregularities extends from a few centimeters to thousands of kilometers (Basu et al., 1978; Hysell and Burcham, 1998). Irregularity structures with scale sizes greater than about 100 km, between 10 km and 100 m, and less than 100 m, respectively, have

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been classified as large, intermediate, small-scale structures (Lühr et al., 2014). From Rino et al. (2016), the large-scale structures encompasses the ionosphere background and the processes of quasi-equilibrium that sustain it, the intermediate-scale includes the significant depletions of ESFs, while the small-scale regime includes structure in the diffusion range, which supports the radar backscatter that delineates plumes. Intermediate-scale plasma structures are responsible for VHF signal fluctuations (e.g., Bhattacharyya et al., 2003).

The general characteristics of irregularities at different scales have been obtained previously from ground-based and in situ satellite observations via power spectrum analysis procedures (e.g., Su et al., 2001; Le et al., 2003; Banola et al., 2005; Singh et al., 2006; Wernik et al., 2007; Rodrigues et al., 2009; Nishioka et al., 2011; Kakad et al., 2012; Chatterjee et al., 2013; Lühr et al., 2014; Rino et al., 2016). Su et al. (2001) examined the behavior of horizontal structures in equatorial spread F near 600 km altitude using ion density and vertical ion drift velocity sampled at 1024 Hz from the Republic of China Satellite 1 (ROCSAT-1). The 1024-Hz measurements of plasma density showed that the plasma irregularity spectrum can be approximated by a power law with constant spectral indices (Su et al., 2001). However, ROCSAT-1 recorded plasma density data at 1024 Hz for only short periods of time (Lühr et al., 2014). Banola et al. (2005) analysed power spectral densities of VHF amplitude scintillation measurements recorded from the geostationary satellite FLEETSAT in the Indian region. They observed that the power spectral slopes are shallower for the scintillation at the generation phase and steeper towards the decay phase, which indicated the erosion of smaller scale sizes towards the decay phase. Singh et al. (2006) also used FLEETSAT to analyze the statistical features of overhead ionospheric irregularities at low latitude station, Varanasi. They carried out spectral analysis and the derived spectral index ranged between -2 and -8 . Singh et al. (2006) also observed spectra with double slopes, which indicate an inner and an outer region for the power-law irregularities. Kakad et al. (2012) also used FLEETSAT measurements to perform power spectral analysis of weak scintillations during geomagnetically quiet and disturbed days over India and they concluded that the power spectral index may be used to identify the freshly generated EPBs triggered by magnetic activity. Wernik et al. (2007) presented a scintillation climatological model for the Northern Hemisphere high-latitude ionosphere, which made use of the Dynamics Explorer 2 (DE-2) retarding potential analyzer (RPA) plasma density data, IRI ionosphere model, and the phase screen propagation model. They derived spectral index from DE-2 plasma density data and they were able to reproduce successfully the observed scintillation intensity diurnal and seasonal variations. Power spectrum analysis is a useful tool to develop an idea of how ionospheric irregularities evolve (Nishioka et al., 2011; Lühr et al., 2014). According to Rino's phase screen scintillation model, the

spectral index, obtained from power spectral analysis, is a key parameter for the correct determination of the scintillation level (Rino, 1979). Therefore, to derive scintillation levels, it is essential to examine the spectral index relationship to different geophysical conditions (Wernik et al., 2007). Although the spectral characteristics of ionospheric irregularities have been extensively studied for several decades, there are still some important and challenging tasks that need to be performed to improve current understanding of their detailed spatial/temporal structures. Nishioka et al. (2011), Rodrigues et al. (2009), Rino et al. (2016) used Communication Navigation Outage Forecasting System (C/NOFS) satellite measurements to investigate the spectrum of density irregularities. Rodrigues et al. (2009) analysed irregularities with scale-sizes in the intermediate (0.1–10 km) and transitional (10–100 m) domains observed when C/NOFS was flying through a large equatorial spread F (ESF) depletion on the night of October 9–10, 2008 over South America. Rodrigues et al. (2009) suggested the operation of a diffusive sub-range in the density power spectra and the possibility of an inertial plasma regime being observed at relatively low altitudes as a result of the long-lasting solar minimum conditions. Nishioka et al. (2011) compared plasma density disturbances measured by a Planar Langmuir Probe (PLP) instrument on the C/NOFS satellite with VHF scintillation activity at Ancon near Jicamarca during October 2008. Nishioka et al. (2011) observed that the power law spectra within the plasma bubbles showed two slopes: the low frequency slope being $\sim -5/3$ and the high frequency ~ -5 with a break around wavelength of 70 m. Nishioka et al. (2011) suggested that this particular type of two-slope spectra may be related to the extremely low solar activity and its impact on ion composition and temperature. Rino et al. (2016) identified intermediate-scale two-component spectra as prominent features in the most highly disturbed C/NOFS passes. Their results confirmed a known inverse correlation between turbulent strength and spectral index. However, C/NOFS (including ROCSAT-1) sampled bubbles in the zonal direction because of its low inclination orbit, and therefore only the horizontal spectrum were determined. Lühr et al. (2014) checked the properties of signal spectra got from Challenging Minisatellite Payload (CHAMP) 50-Hz magnetic field measurements at intermediate-scale for the years from 2000 to 2010 and they observed that the signal spectrum can be approximated by a power law. Over the frequency range 1–25 Hz, Lühr et al. (2014) also observed spectral indices between -1.4 and -2.6 with peak occurrence rates around -1.9 , and there was a weak dependence observed of the spectral index on local time. The spectral characteristics presented by Lühr et al. (2014) were derived mostly under solar maximum conditions.

The European Space Agency's (ESA's) Swarm mission offers an opportunity to also examine the spectral characteristics of ionospheric irregularities in the meridional direction along its nearly polar orbital paths. The Swarm satellites record electron density at a frequency of 16 Hz

using the Electric Field Instrument (EFI) faceplate (Knudsen et al., 2017). The physical processes that cause small-scale ionospheric irregularities can be recognized by means of high-resolution measurements and these may also improve on the accuracy of radio wave propagation models through irregularity structures (Rodrigues et al., 2009; Nishioka et al., 2011; Lühr et al., 2014). Therefore, the high-resolution electron density data from the Swarm faceplate are appropriate for intermediate-scale structure analysis down to 500 km scale length. In this study, we used the high sampling rate (16 Hz) electron density measurements made by Swarm to investigate the nearly vertical spectrum of density irregularities. The study covers the years from 2014 to 2018, corresponding to the descending phase of solar cycle 24, when the measurements of 16 Hz electron density were available. Our investigations aimed at determining the spectral characteristics of sub-kilometer plasma density structures. In particular, we present a statistical study of power spectral indices as derived from the Swarm constellation faceplate measurements.

The paper is organized in the following order: In Section 2, we briefly describe the data and methods of analysis. In Section 3, the results of our analysis are presented and discussed with regards to prior reports. The main conclusions are summarized in Section 4.

2. Data and methods

The Swarm mission is made up of three satellites (Swarm A, B, and C) with an orbital speed of around 7.5 km s^{-1} in polar orbits. Each satellite has a faceplate installed on the ram side in addition to other payloads. Detailed description of the Swarm satellites and their various payloads are provided by Friis-Christensen et al. (2006) and Knudsen et al. (2017). The faceplate measures electron density (N_e) at a frequency of 16 Hz. The N_e is derived from the faceplate current assuming that it is carried by ions hitting the faceplate due to the orbital motion of the spacecraft (Buchert, 2016). By October 2018, Swarm A and C were orbiting next to each other in polar orbits (inclination angle of 87.35°) at about 1.4° longitudinal spacing and 448 km altitude above sea level over the low-latitude region, and Swarm B was orbiting at an altitude of about 512 km (inclination angle of 87.75°). Data sets measured by Swarm can be downloaded from <http://earth.esa.int/swarm>.

Only Swarm passes for which the Local time at the equator crossing was between 1800 and 0600, i.e. on the night side, were considered because ionospheric irregularities in the low-latitudes are a nighttime phenomena. For each of these passes, only the part with the quasi-dipole latitude (QLat) within the range $\pm 30^\circ$ was used. All geographical longitudes were considered during the analysis and therefore, the region spanning the whole low-latitude region was considered in this study. In order to avoid contamination by other effects during magnetic storms we have

rejected events from times with $K_p > 3$. After setting the defined limitations, the resulting list of Swarm passes were used as a basis for our analysis. The 16 Hz N_e data were first split into 8-s long segments (e.g. Nishioka et al., 2011) with 4-s overlap. Due to the fast motion of Swarm (velocity $\approx 7.5\text{ km/s}$), we can assume the irregularity structures to be frozen in the flow (Taylor, 1938) over the period of 8-s used for spectral analysis. Each segment was first detrended by removing the linear variation as given by a linear fit to obtain the residual, ΔN_e . The resulting residuals were subjected to further analysis. A hanning window was applied to the time series to avoid spectral artifacts such as energy leakage (Press et al., 1992; Liu et al., 2012). The next procedure was to apply Fast Fourier Transform (FFT) technique to obtain the power spectrum. Some previous studies (e.g. Kil and Heelis, 1998; Rodrigues et al., 2009; Nishioka et al., 2011) applied FFT to the normalized deviations ($\Delta N_e/N_e$), while others applied it to the absolute deviation (ΔN_e) (e.g. Lühr et al., 2014). From Huang et al. (2014) and Aol et al. (2020a), occurrence of irregularities based on absolute deviation is consistent with that of scintillation. Therefore, in this study, we applied FFT to the absolute deviation. The FFT was applied to the absolute deviation ΔN_e within a moving window of 8-s. Sampling at 16 Hz provides 128 samples during 8-s. The Swarm satellites cover about 60 km during 8-s considering the velocity of 7.5 km/s. Therefore, the maximum span of the spectrum is about 6.7 rad/km (frequency, $f = 50.25\text{ Hz}$). The FFT window is moved forward in 4-s steps, providing some signal overlap.

The standard deviation of the residuals was determined to represent the density perturbation, $\text{std}(\Delta N_e)$. There is no standard threshold definition of how large $\text{std}(\Delta N_e)$ must be to identify plasma irregularities (Huang et al., 2014; Wan et al., 2018). However, the period considered in this study was characterized by low solar activity, and the recorded ionospheric irregularities were very weak. Therefore, a threshold value of $\text{std}(\Delta N_e) = 1 \times 10^{-10}\text{ m}^{-3}$, similar to that adopted by Huang et al. (2014) and Aol et al. (2020b), was selected to provide a reasonable irregularity event identification at the small-scales and the relatively low Swarm altitudes during the study period. The results are presented and discussed in the following section.

3. Results and discussions

Fig. 1 presents an example of one equator crossing for Swarm A on 2014–10–06. Panel (i) of Fig. 1 shows large N_e drop-outs along the satellite pass and these are dominant between about $\pm 10^\circ - \pm 20^\circ$ QLat. The stated QLat range corresponds to the approximate location of the Equatorial Ionization Anomaly (EIA) belts where ionospheric irregularities are known to occur. Small-scale structures can also be observed inside some density depletions in panel (i) of Fig. 1 because of the good temporal resolution of the 16 Hz N_e measurements. Close inspection of Swarm

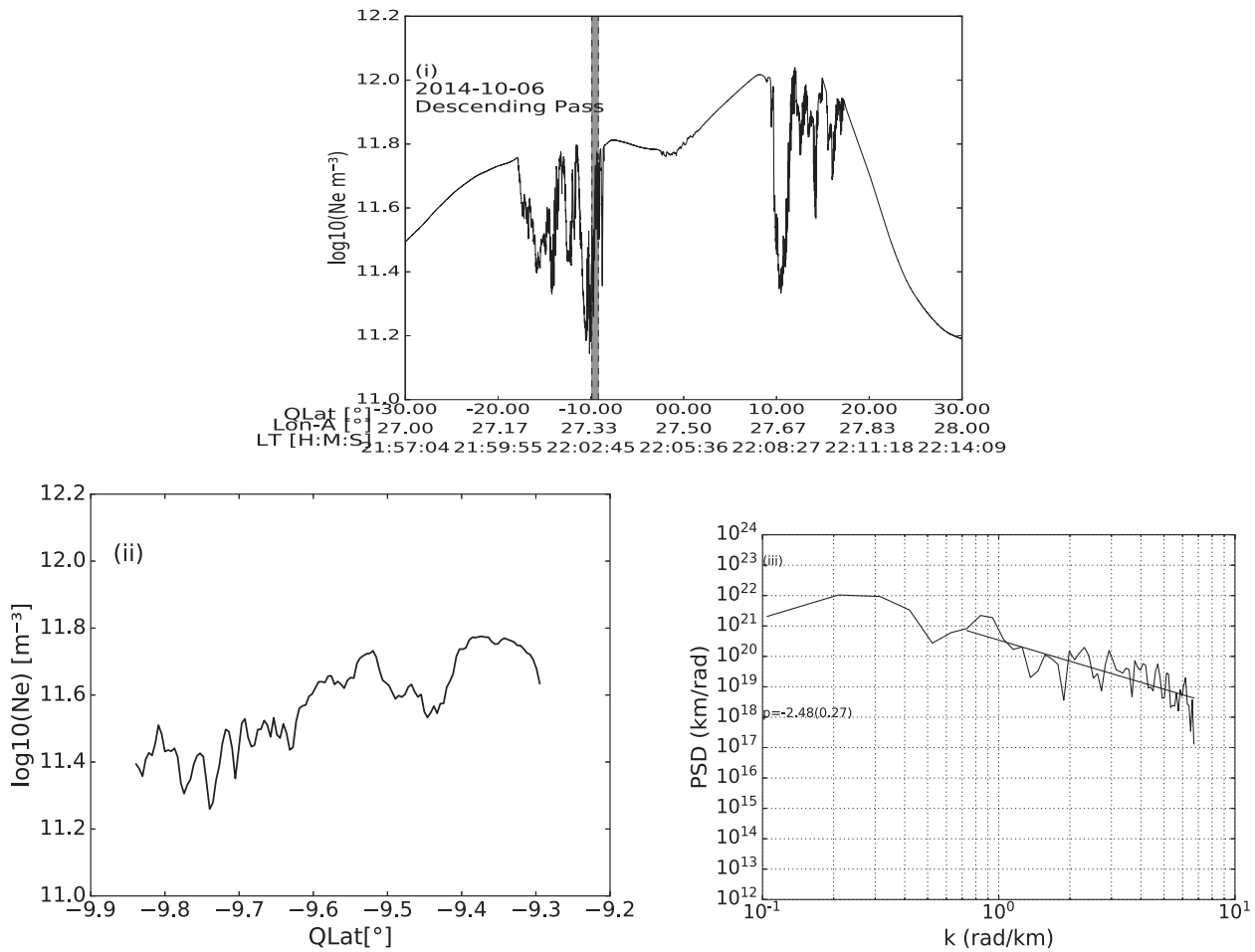


Fig. 1. (i) Swarm A pass on 2014–10-06. (ii) 8-s N_e segments. (iii) Power Spectral Density (PSD) of a 8-s long segment. The values of the spectral index p estimated by linear least square fitting are indicated and the uncertainty in the slopes are provided in parenthesis for the slope.

A satellite pass in panel (i) of Fig. 1 shows N_e depletions also close to the quasi-dipole equator. The Rayleigh–Taylor Instability (RTI) is the most recognized driving mechanism for the formation of ionospheric irregularities in the low-latitudes (Woodman and La Hoz, 2012; Abdu, 2005; Kelley, 2009). The lower ionospheric layers, E and lower F regions, recombine rapidly during the night compared to the top layer. This creates a sharp vertical gradient of plasma density directed upwards, contrary to the gravitational force’s direction of action. Such an arrangement is unstable and this causes irregularities in the bottom F region. The irregularities drift up, intensifying and creating more complex plasma structures that extend to higher altitudes. The structures are elongated along magnetic field lines (Woodman and La Hoz, 2012; Abdu, 2005; Kelley, 2009).

An example of 8-s long N_e segment, corresponding to the gray region in panel (i), is shown in panel (ii) of Fig. 1 and the resulting PSD is presented in panel (iii). The PSD is plotted as a function of the wave number k ($k = \omega/v$, $v = 7.5 \text{ km s}^{-1}$ is the speed of the Swarm satellites, ω is the angular frequency). Panel (iii) of Fig. 1 shows

that regions in the spectra tend to follow the power law ($P(k) \propto k^p$). The power law relation has also been observed for previous missions (e.g., Yeh and Liu, 1982; Dyson et al., 1974; Su et al., 2001; Wernik et al., 2003; Wernik et al., 2007; Rodrigues et al., 2009; Nishioka et al., 2011; Lühr et al., 2014). Previous observations revealed the presence of a spectral break around 100 Hz ($\sim 90 \text{ m}$ wavelength). For example, Rodrigues et al. (2009), Nishioka et al. (2011), Rino et al. (2016), Rino et al. (2018) used ion density measurements made by the PLP on board C/NOFS at a sampling rate of 512 Hz and they observed spectral breaks. Su et al. (2001) also observed spectral breaks using ion density and vertical ion drift velocity sampled at 1024 Hz from the ROCSAT-1 satellite. In the example presented in panel (iii) of Fig. 1, there is no clear evidence of a spectral break, as the range considered here is well below the typical break frequency reported in the literature.

Fig. 2 shows a summary of the irregularity intensity and spectral characteristics for Swarm A equator crossing on 2014–10-06. Inspection of Fig. 2 allows to identify the relation between spectral characteristics and ionospheric irregularities. There were several packets of large $\text{std}(\Delta N_e)$

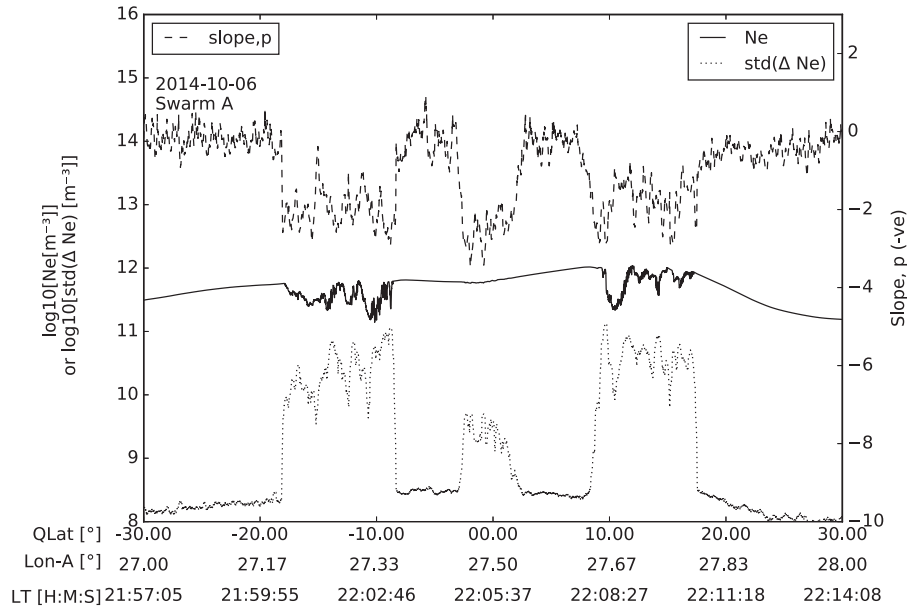


Fig. 2. Irregularity structures observed by Swarm A for a single pass on 2014–10-06. Panels (a) shows the N_e variation at 16 Hz in logarithmic scale, absolute N_e perturbations ($\text{std}(\Delta N_e)$), spectral index or spectral slope p as functions of QLat, Geographic longitude (Lon), and Local Time (LT).

($> 1 \times 10^{10} \text{ m}^{-3}$) encountered by Swarm A along its path. The spectral index appeared to be steeper in latitude ranges where ionospheric irregularities were observed. For irregularities encountered nearest to or exactly at the quasi-dipole equator, p was even more steeper reaching values lower than -3 . In general, for low values of $\text{std}(\Delta N_e)$, p becomes small. The observed anti-correlation between $\text{std}(\Delta N_e)$ and p agrees with previous studies (e.g., Kelley, 2009; Nishioka et al., 2011).

To determine the probability of occurrence of p , they were obtained for the period from 2014 to 2018 for only irregularly disturbed Swarm passes when the 16 Hz N_e data was available. The percentage occurrences of p are pre-

sented in Fig. 3 for Swarm A, C, and B, independently. In general, p was observed to cover the range -6.0 to $+1.0$ in Fig. 3, with a peak in percentage occurrence centered at around $p = -2.5$. Le et al. (2003) presented results from short intervals of ROCSAT-1 burst mode measurements at 1024 Hz sampling and the plasma depletion showed a peak in spectral index of about -1.8 in the frequency range 1–100 Hz. After studying the spectral traits of scintillation producing ionospheric irregularities recorded at low-latitude station Varanasi during January 1991 to December 1993 and April 1998 to December 1999 using the 250 MHz radio beacon from geostationary satellite FLEETSAT, Singh et al. (2006) showed that the power law index for irregularities are in the range of -2.0 to -8.0 with the mean value of -4.0 . Patel et al. (2011) found that spectral slope of -2.0 had the highest percentage occurrence using Stretched Rohini Satellite Series C2 (SROSS-C2) data. Lühr et al. (2014) obtained p from the high-resolution CHAMP magnetic field measurements over the frequency range 1–25 Hz and they observed spectral indices between -1.4 and -2.6 with peak occurrence rate around -1.9 , while Wernik et al. (2007) obtained p for the plasma density data recorded by the DE-2 satellite within the frequency range of 1–20 Hz and a peak in percentage occurrence of p was within the range of -1.0 and -2.5 . Rodrigues et al. (2009) found that the spectral slopes at intermediate scale-sizes was ≈ -1.66 using C/NOFS ion density and electric field measurements recorded on October 9–10, 2008. In general, the results presented in previous studies fits well in the p range presented in Fig. 3.

The spectral index may provide some information about the electrodynamics involved in the evolution of density irregularity structures. According to McDaniel and

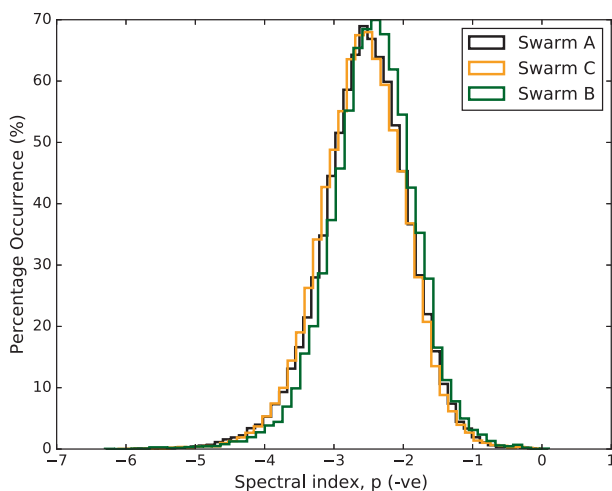


Fig. 3. Percentage occurrence of the spectral indices obtained by linear fit to the PSD in log-log scale for Swarm A, C, and B for the years from 2014 to 2018.

Hysell (1997), the governing processes are either controlled by ion/neutral collisions or by ion inertial effects. The authors show for a number of events recorded by the DE-2 spacecraft that in cases when inertial effects become important p takes the value -1.667 which is within the range observed in Fig. 3. This indicates a special type of inertial range turbulence during the evolution of ionospheric irregularities. It is characterized by a fast upward expansion of the bubble. Within the inertial regime, the polarization currents are larger than the Pederson currents. Pederson currents slow down the expansion velocity due to energy dissipation (McDaniel and Hysell, 1997; Lühr et al., 2014). Two-component spectra have been observed for previous missions (e.g., Rodrigues et al., 2009; Nishioka et al., 2011; Rino et al., 2016) and these were distinguished by a spectral break at around $k = 90 \text{ rad/km}$ (or $\lambda = 70 \text{ m}$). The differences in the slopes indicate that the irregularities were formed by different processes (Nishioka et al., 2011). As mentioned earlier, the maximum span of the PSDs in this study was below 70 m wavelength and therefore, a spectral break could not be determined. As a next step, we looked at a possible dependence of the spectral index distribution on various geophysical parameters.

The $16 \text{ Hz } N_e$ database for the years from 2014 – 2018 was enough to check the distribution characteristics of p with respect to Local Time (LT), latitude, and longitude. The LT variation of p is presented in Fig. 4 for Swarm A, C and B, separately. The overlaid contour lines indicate densities of data points. Fig. 4 shows spectral indices occurring frequently between 20:00 LT and 22:00 LT for Swarm A, B, and C in panels (a)–(c) with a single peak centered at about -2.5 . Lühr et al. (2014) presented local time distribution of spectral indices of intermediate-scale structures of equatorial plasma irregularities based on magnetic CHAMP observations and they observed a single peak centered at around -1.9 occurring between 20:00 LT and 22:00 LT. Wernik et al. (2007) also determined local time variation of p obtained from DE-2 satellite electron density measurements at a frequency of 64 Hz . Because of insufficient data, it was difficult to reveal any systematic magnetic time variations at low-latitudes by Wernik et al. (2007).

For comparison, we also determine the LT distribution of ionospheric irregularities quantified by $\text{std}(\Delta N_e)$ and this is presented in Fig. 5 for Swarm A, B, and C in panels (a) to (c), respectively. The LT distribution of p shown in Fig. 4 follows the same trend as that of $\text{std}(\Delta N_e)$ presented in Fig. 5. Majority of equatorial ionospheric irregularities are known to peak within the time sector 20:00 LT to 22:00 LT and then they decay linearly with local time, decreasing towards sunrise to fundamentally zero (e.g., Kil and Heelis, 1998; Su et al., 2006; Stolle et al., 2006; Xiong et al., 2016; Burke et al., 2004; Wan et al., 2018). The containment of p to the 20:00 LT – 22:00 LT time sector suggests that our observations are related to the early stage of development of ionospheric irregularities. The decrease of spectra after 22:00 LT till 06:00 LT may be related to the decay of the perturbation electric field associated with the RTI (Lühr et al., 2014).

The QLat distribution of p was also examined and the results are shown in panels (a)–(c) of Fig. 6 for Swarm A, C, and B, independently. The figure shows a peak in the distribution of p centered at around -2.5 at the approximate location of the EIA belts. To compare the latitudinal distribution of p presented in Fig. 6 with that of $\text{std}(\Delta N_e)$, we refer to the results shown in Fig. 5. The $\text{std}(\Delta N_e)$ values are high around the northern and southern EIA belts that is to say, their distribution is almost symmetrical around the quasi-dipole equator and this is similar to the distribution of p in Fig. 6. The symmetrical distribution of ionospheric irregularities about the quasi-dipole equator has also been observed in earlier studies (e.g., Stolle et al., 2006; Xiong et al., 2012; Aol et al., 2020a). Also, From Fig. 5, the quasi-dipole equator is not completely void of ionospheric irregularities, but their magnitudes are low, compared to those observed at the EIA belts. In other words, $\text{std}(\Delta N_e)$ increases farther away from the equator. In general, there is a non-uniform increase of p and $\text{std}(\Delta N_e)$ from the quasi-dipole equator to the EIA latitudes. Bolaji et al. (2017) and Mungufeni et al. (2018) observed non-uniform EIA peaks in the south and north of the magnetic equator, respectively using GPS receivers installed along the African longitude. Bolaji et al. (2017) suggested

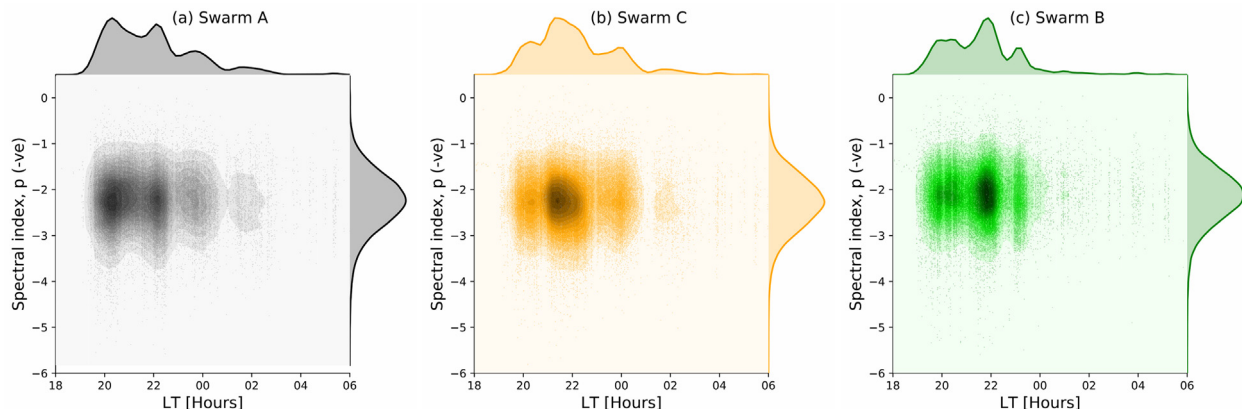


Fig. 4. Local time dependence of spectral index p for Swarm A, C, and B for the years from 2014 to 2018 in panels (a) to (c), respectively.

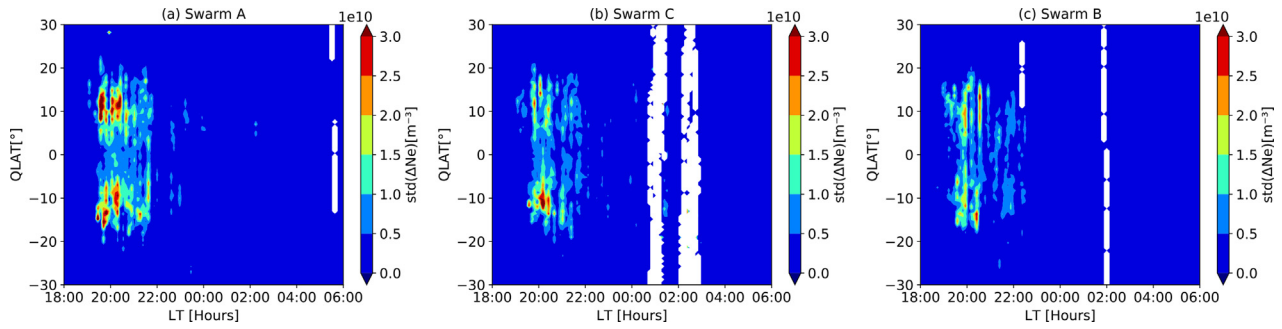


Fig. 5. The variation of $\text{std}(\Delta N_e)$ as a function of LT and QLat during 2014 to 2018 for Swarm A, C, and B in panels (a) to (c), respectively. In each.

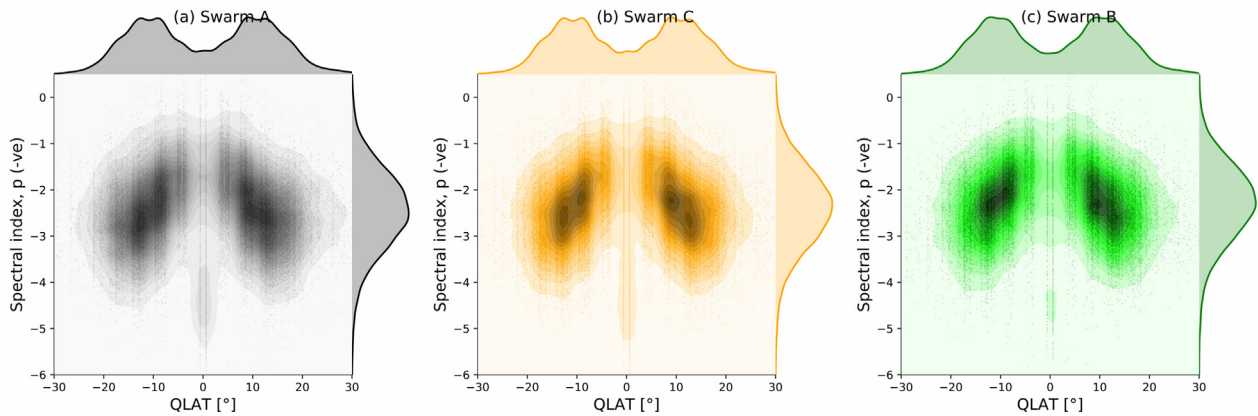


Fig. 6. Latitudinal distribution of spectral index p for Swarm A, C, and B in panels (a) to (c), respectively for the years from 2014 to 2018.

that these scenarios could result from inconsistent transportation of plasma from the quasi-dipole equator to higher latitudes.

Among other parameters, the gradient of electron density controls the growth rate of equatorial ionospheric irregularities (Muella et al., 2010). Therefore, we also checked on the distribution of electron density gradient to compare with the results presented in Fig. 6. Fig. 7 shows the distribution of electron density gradient, ∇N_e as a function of QLat and LT for Swarm A, C, and B in panels (a) to (c), respectively. To determine the ∇N_e along the satellite tracks, the N_e depletion was divided by the corresponding latitudinal distance in degrees. Fig. 7 shows that the peak intensity of p is associated with regions of

highest electron density perturbations and steepest electron density gradients. The electron density gradient is seen to increase further away from the equator and peaks at the approximate latitudes of the EIA belts. Lühr et al. (2014) observed highest probability of occurrence for $p = -1.9$ occurring about $\pm 15^\circ$ magnetic latitude away from the dip equator using CHAMP. From Lühr et al. (2014), the region close to the magnetic equator was practically free of intermediate scale events. Lühr et al. (2014) suggested that CHAMP flew more or less along the magnetic flux tubes in the vicinity of the dip equator (i.e, the angle between CHAMP orbital path and the magnetic flux tubes $\approx 0^\circ$) and thus it could not sample meridional plasma structures.

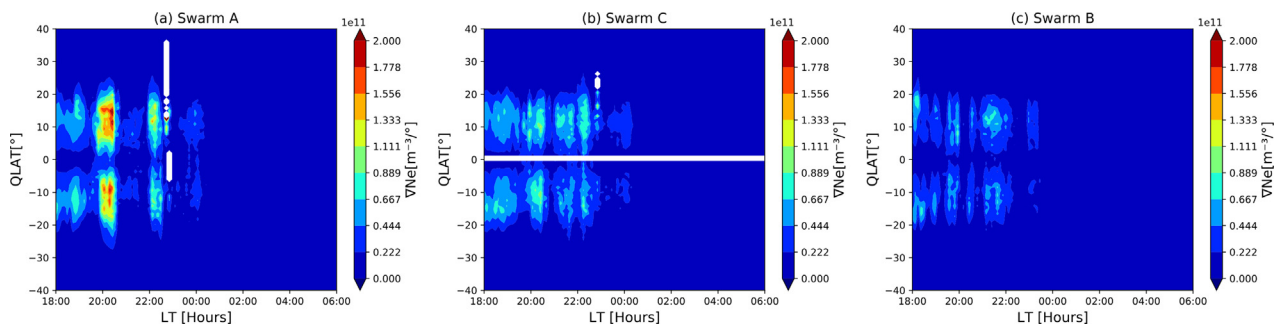


Fig. 7. Distribution of electron density gradient (∇N_e) as a function of QLat and LT for Swarm A, C, and B in panels (a) to (c), respectively.

In this study, we also checked the variations in the angle between the Swarm orbital paths and the magnetic flux tubes ($\angle(B, v)$). Two dimensional histograms showing latitudinal distribution of $\angle(B, v)$ are shown in Fig. 8 for Swarm A, C, and B, independently. To determine $\angle(B, v)$, the three components of the magnetic field measurements by the Vector Field Magnetometer (VFM) at 1 Hz resolution were used in North-East-Center (NEC) coordinate system (i.e., $\angle(B, v) = \arccos(\mathbf{B} \cdot \mathbf{v} / |\mathbf{B}| |\mathbf{v}|)$). $\angle(B, v)$ is not always equal to 0° near the quasi-dipole equator. Therefore, Swarm records irregularity structures near the quasi-dipole equator irrespective of whether their paths are inclined at angles $\geq 0^\circ$ to the magnetic flux tubes near the quasi-dipole equator. From Dao et al. (2011), at the magnetic equator, the $\mathbf{B}$ field has no dip angle. However, off the magnetic equator, the $\mathbf{B}$ fields have finite dip angles. Therefore, satellite orbits cannot follow closely along field lines (Dao et al., 2012). This therefore implies that Swarm has the capability to sample meridional structures in the vicinity of the quasi-dipole equator as shown in Fig. 8. To further enhance on the interpretation of the relationship between $\angle(B, v)$ and p , Fig. 9 was generated. From Fig. 9, a peak in p is observed and this is clustered between about $40^\circ \leq \angle(B, v) \leq 20^\circ$. For all three satellites spectra tend to be steeper (spectral index more negative) for larger $\angle(B, v)$. Roughly, p increases from about -2 to -2.4 when $\angle(B, v)$ changes from 20 to 30° . This is consistent with structures that are elongated along the background magnetic field and local anisotropic turbulence at scales of a

few km. 3D simulations of equatorial plasma bubbles had shown a similar anisotropy as observed by Yokoyama et al. (2014) and Yokoyama (2017). In general, the results show a weak correlation between p and $\angle(B, v)$ and this may be attributed to limited data. However, there is a clear anticorrelation between p and the $\angle(B, v)$, suggesting that the turbulence is reduced when the spacecraft are sampling along the magnetic field flux tubes (Horbury et al., 2008).

In this study, we also checked the longitudinal variation of p and the results are shown in Fig. 10 for Swarm A, C and B in panels (a)–(c) respectively. To compare with the longitudinal distribution of sub-kilometer irregularity events, Fig. 11 shows the distribution of $\text{std}(\Delta N_e)$ as a function of QLat and longitude for each Swarm satellite independently in panels (a) to (c). From Fig. 10, the peak value of $p = -2.5$ is observed in the South American-Atlantic-African regions (-120° to $+60^\circ$ longitude) and it is generally low in the Asian-Pacific region. In particular, the observed peak of p was centered at around -50° longitude. In general, from Fig. 11, the longitudinal distribution of $\text{std}(\Delta N_e)$ follows the same pattern as that of p with highest $\text{std}(\Delta N_e)$ values at the longitudinal range of -120° to 60° . Furthermore, from Fig. 11, the high $\text{std}(\Delta N_e)$ values are commonly observed within the QLat range of $\pm 15^\circ$ to $\pm 20^\circ$, which is the location of the EIA. Moderately high values of $\text{std}(\Delta N_e)$ can also be observed at the quasi-dipole equator from Fig. 11. This implies that the quasi-dipole equator is not completely void of ionospheric

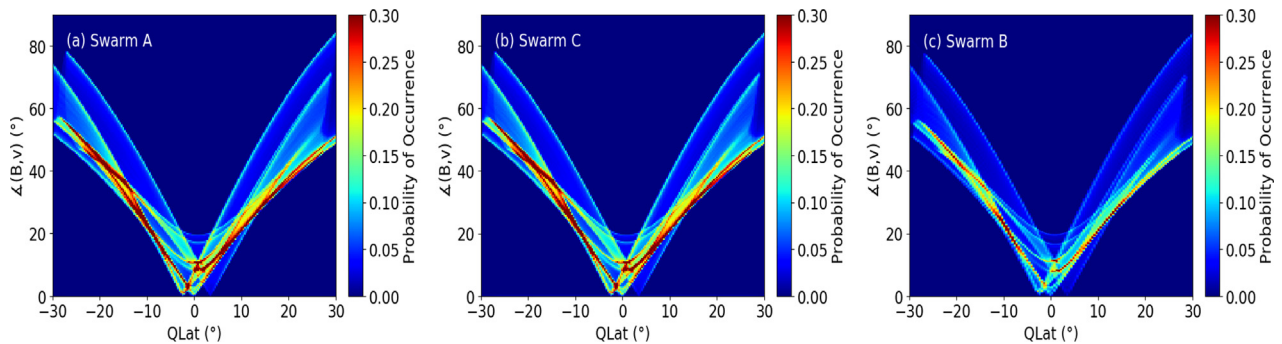


Fig. 8. Latitudinal distribution of angle between magnetic field and satellite path $\angle(B, v)$ for Swarm A, C, and B, respectively for the years from 2014 to 2018.

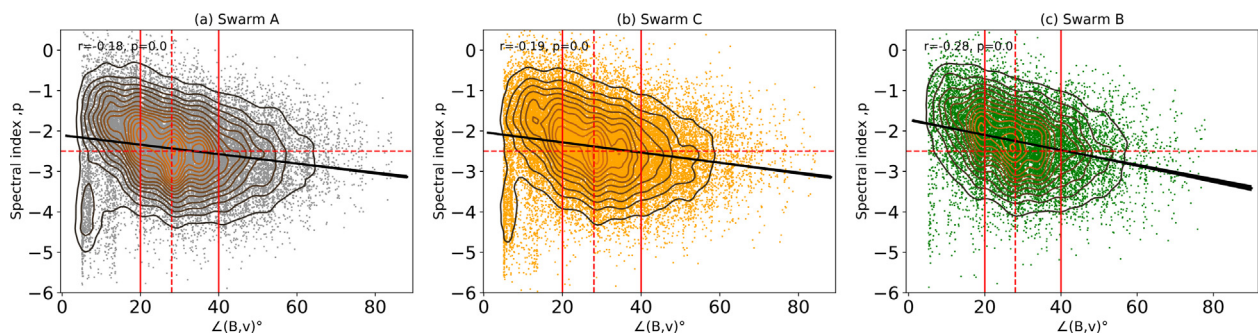


Fig. 9. Distribution of spectral index p and $\angle(B, v)$ for Swarm A, C, and B in panels (a) to (c), respectively.

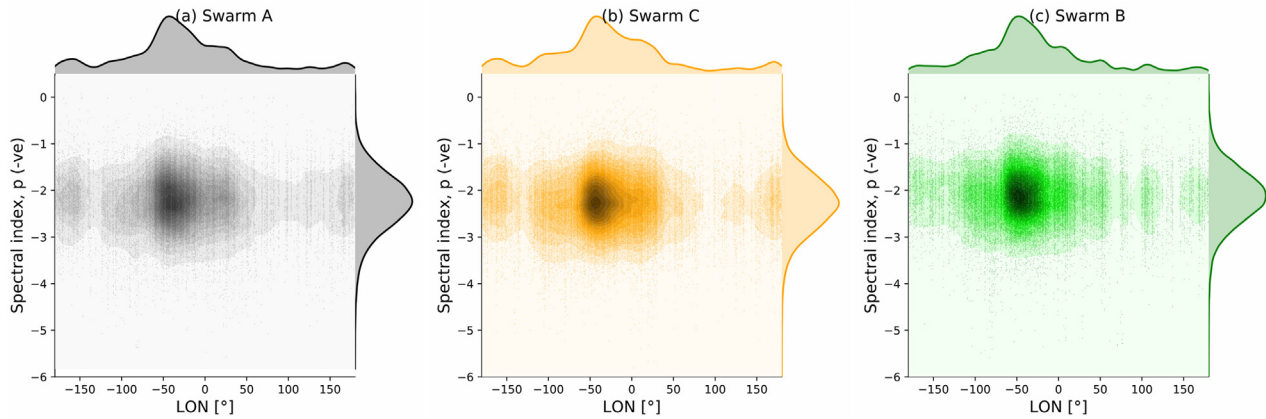


Fig. 10. Longitudinal distribution of spectral index p (panel (a)–(c)) for Swarm A, C, and B, respectively for the years 2014 to 2018.

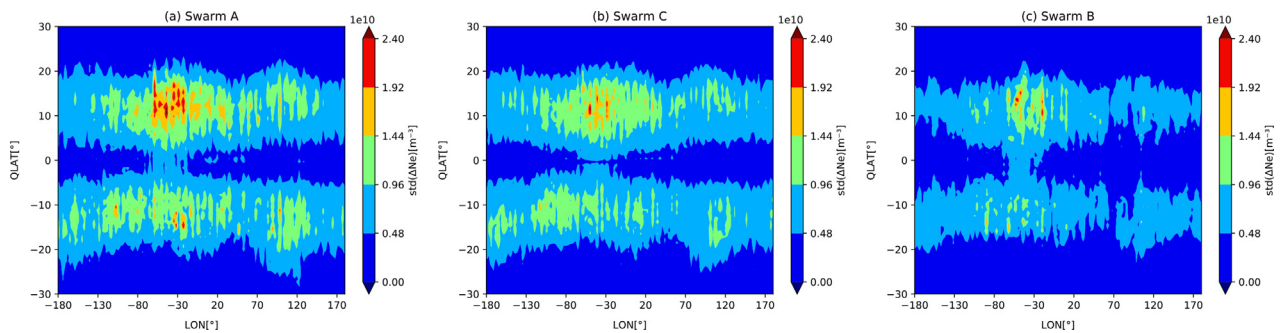


Fig. 11. Distribution of $\text{std}(dN_e)$ (panel (a)–(c)) as a function of QLat and longitude for Swarm A, C, and B, respectively for the years from 2014 to 2018. The time period considered is 1800 LT to 0600 LT.

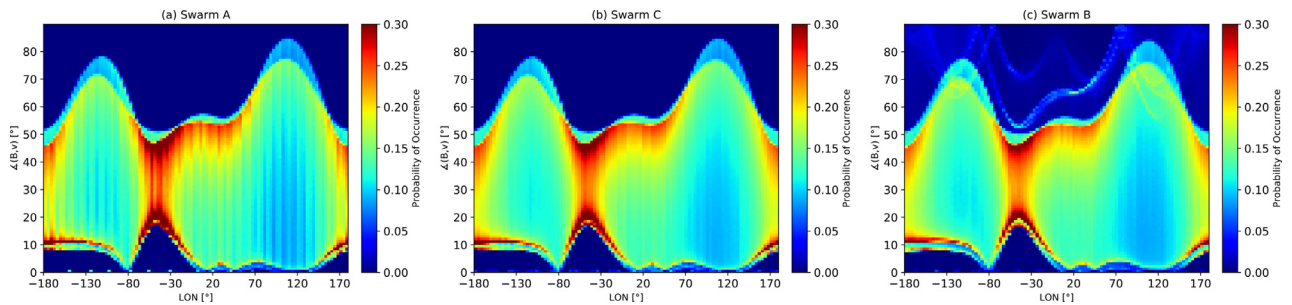


Fig. 12. Longitudinal distribution of angle between magnetic field and satellite path $z(B, v)$ for Swarm A, C, and B in the first, second, and third columns, respectively for the period from October 2014 to October 2018.

irregularities. The same pattern in longitudinal distribution of occurrence of ionospheric irregularities was observed in earlier studies (e.g. Kil and Heelis, 1998; Park et al., 2005; Stolle et al., 2006; Xiong et al., 2012; Lühr et al., 2014). The South American-Atlantic sector corresponds to the longitudinal range where the magnetic declination is negative. This shows that the magnetic declination angle is a significant factor in the occurrence of irregularities in plasma density (Kil and Heelis, 1998). A possible dependence of longitudinal distribution of p on the angle between the magnetic flux tubes and the satellite path was also checked and the results are shown in the fourth panel Fig. 12. At around -50° longitude, $z(B, v)$ is hardly zero, near where steep gradients and peak spectral index are found. The

$z(B, v)$ varied frequently between 20° and 50° . As mentioned earlier, this longitude range corresponds to the South American-Atlantic sector where the magnetic declination is negative. Over the Indian sector (60° to 150° longitude), $z(B, v)$ is mostly greater than 50° . The observations made in Fig. 12 may imply that Swarm frequently encounters irregularities in longitudinal sectors where $z(B, v)$ is between 20° and 40° .

4. Conclusions

In this paper, the spectral characteristics of ionospheric irregularities were examined for the polar orbiting Swarm satellites using the 16 Hz N_e measurements for the years

from 2014 to 2018 when the data was available. Swarm has provided good data coverage to examine the spectral characteristics of ionospheric irregularities. The study period considered coincided with the descending phase of solar cycle 24. This is the first comprehensive study of the detail spectral characteristics of plasma structures along the meridional profiles of the Swarm satellites. The findings of this study are summarized below:

- The spectral characteristics of the ionospheric irregularities can be approximated by a power law, $P(k) \propto k^p$. In the considered frequency range, 1–50.25 Hz, a peak spectral index of about $p = -2.5$ was obtained.
- The peak spectral index occurred frequently between 20:00 LT and 22:00 LT and then decreased gradually after about 22:00 LT till 0600 LT. This followed the same trend as the local time distribution of percentage occurrence of ionospheric irregularities. The containment of p to the 20:00 LT - 22:00 LT time sector suggested that the observations were related to the early stage of development of ionospheric irregularities. The decrease in peak spectra from about 22:00 LT to 06:00 LT may be related to the decay of the perturbation electric field associated with the RTI.
- The QLat distribution of p showed a peak centered at the EIA belts. This followed the same trend as the QLat distribution of $\text{std}(\Delta N_e)$. The density of p seemed to be larger in the southern hemisphere compared to the northern hemisphere and may be because the ambient magnetic field strength is weaker the southern EIA. A non-uniform increase of p from the magnetic equator to the EIA latitudes was also observed and this may have implied an inconsistent transportation of plasma to higher latitudes.
- The peak of p was observed in the South American-Atlantic-African regions and it was generally low in the Asian-Pacific region. The longitudinal distribution of percentage occurrence of ionospheric irregularities followed the same pattern as that of p . The South American-Atlantic sector corresponds to the longitudinal range where the magnetic declination is very negative. This shows that the magnetic declination angle is a significant factor in the creation of irregularities in plasma density.
- A parameter which may be of interest in determining whether polar orbiting Swarm satellites encounter ionospheric irregularities is the $\chi(B, v)$. In this study, it was observed that highest percentage of occurrence of ionospheric irregularities and the peak in p was obtained only when the $\chi(B, v)$ was between 20° and 40° . Over this range of angles PSD spectra steepen with increasing $\chi(B, v)$ (p becomes increasingly negative), consistent with local anisotropic turbulence at scales of a few km.

The Swarm faceplate data set has revealed a lot of detailed spectral features of sub-kilometer electron density variations associated with plasma bubbles. Many of the

observations confirm previous reports, but other findings need further investigations. The results presented in this paper are important for a better modeling of radio wave scintillation since the intensity of VHF/UHF scintillations observed by ground-based receivers depends on the magnitude and spectral distribution of density fluctuations.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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