

The authors of this manuscript thank the reviewers for the suggestions and comments. In enhancing the quality of the paper, all the remarks we received on this research were taken into consideration and we present our response to each of them individually below. A marked-up manuscript version has also been embedded at the end of this document.

Response to Reviewer 1 comments

General Comments:

- The results shown confirm earlier published findings, and some other analyses do not seem fully consistent (see specific comments). The submitted manuscript provides an excellent report to indicate that identified fluctuations in electron density time series obtained by the TII faceplate technique onboard the Swarm satellites with 16Hz sampling rate are most probably related to equatorial post-sunset plasma irregularities. But it is unlikely that the report enhances present scientific knowledge and evidence.

My major concern is, however, that this analysis does not show any findings based on the 16Hz samplings that could not have been achieved with the 2 Hz samplings onboard Swarm. The authors are encouraged to exploit the high value of the 16 Hz sampling.

– Response:

- This study aimed at checking the capability of the Swarm 16-Hz faceplate electron density measurements for equatorial ionospheric irregularity observations at sub-kilometer scale length. The capacity of the 2 Hz electron density measurements made by the Langmuir Probes on board Swarm are not disregarded in this study. However, as stated in P.2,L.34 and presented in Figure 1 (P.5), high-resolution data enables smaller scale structures to be identified in electron density (Nishioka et al., 2011,<https://doi.org/10.1029/2011ja016446>). As a new aspect which is possibly relevant for especially the small-scale irregularities we have also analyzed the along-track gradient of N_e (as a proxy of the pressure gradient).
- We agree with the reviewer about exploiting further the 16 Hz Swarm electron density measurements. Previously, Alfonsi et al., 2007, <http://dx.doi.org/10.1016/j.asr.2017.05.021> recommended high resolution electron density measurements as input to the WAM model. However, as stated in P.2, L.8-10, the dependence of ionospheric irregularities on the geophysical parameters, remains a problem in modeling their variation for predictive purposes (Yizengaw and Groves, 2018,<https://doi.org/10.1029/2018sw001980>). The results presented in this study, characterize sub-kilometer ionospheric irregularities basing on various geophysical parameters as a first step towards developing a model from Swarm 16-Hz in situ measurements of electron density. Currently, the team involved in this paper are carrying out further research involving modeling of amplitude scintillation from Swarm 16 Hz measurements using the WAM model. We thank the reviewer for the suggestion.

Selected specific comments:

1. **Comment:**The concept of deriving electron density from the TII faceplate technique is an extended product in the concept of the Swarm mission. A bit a more detailed description of the retrieval and the data shall be added, next to referring to "Buchert, S.: Extended EFI LP data FP release notes, ESA Technical Note, 2016." (I did not find the document in the web, and do not know if/where it is accessible.)

Response: The ESA Technical report is accessible via ftp at:

ftp://swarm-diss.eo.esa.int/Advanced/Plasma_Data/16_Hz_Faceplate_plasma_density. More detailed information about obtaining electron density from the TII can also be obtained from Knudsen et al, 2017, doi:10.1002/2016ja022571. The reference Buchert, S. 2016 has been update in the revised manuscript with the ftp link added (see Pg.22 L.21-22). In addition, the following statement has been included in the revised manuscript.

Knudsen et al. (2017) provide more details on how electron density is derived from the LPs and TH.
(see Pg.3 L.14)

2. **Comment:**P2, L1-14: The authors have access to the full Swarm mission data to perform orbital analyses, such as the spacing of Swarm A/C or the local time processing. Alternatively, they may refer to classical papers, such as provided in doi:10.5047/eps.2013.07.001 if needed. You might reconsider, if Kil et al. or Xiong et al. are suitable references in this broad context.

– **Response:**

- We agree with the reviewer that it would be interesting to perform orbital analysis for the available Swarm 16 Hz data set during the period of study. Previously, Zakarenkova et al. (2016),DOI 10.1186/s40623-016-0490-5, presented orbit analysis for Swarm A and B and they stressed the local time difference between Swarm A and B during the period from August 2014 to January 2016. We present a snap shot of their result in Figure ?? . Also,

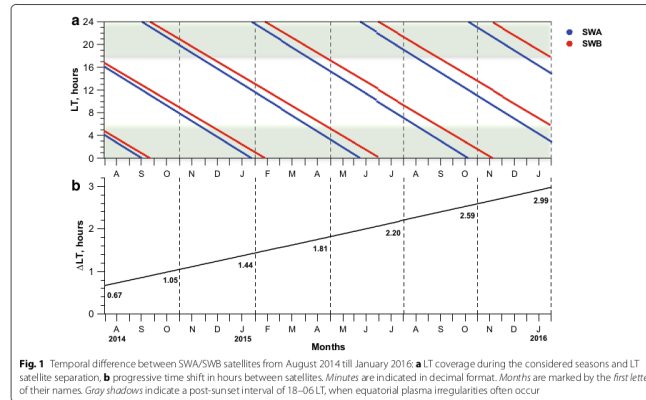


Figure 1. From Zakarenkova et al. (2016),DOI 10.1186/s40623-016-0490-5

Xiong et al (2016),DOI 10.1186/s40623-016-0502-5 presented the evolution of the longitudinal separation and time lag between the Swarm spacecrafts during the early mission phase (December 9, 2013-January 27, 2014) and the final constellation phase (April 17, 2014- September 27, 2015). We also present a snap shot of their results in Figure 9:

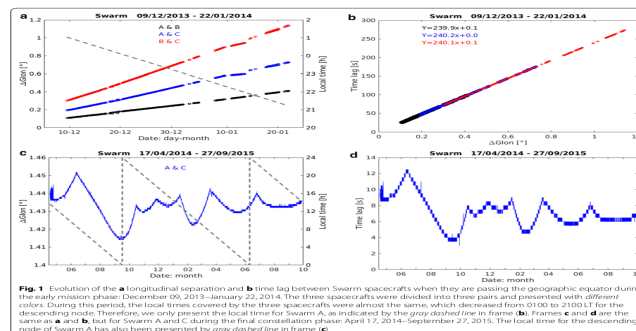


Figure 2. From Xiong et al (2016),DOI 10.1186/s40623-016-0502-5

However, as suggested by the reviewer, the five years of Swarm mission data used in the present study is sufficient for a long term orbital analysis to provide an up to date orbital status. Using five years of Swarm mission data, Claudia Stolle and the Swarm Science Team (2018), (https://cedarweb.vsp.ucar.edu/wiki/images/d/db/2018CEDAR_Monday_Stolle2.pdf) also presented orbital analysis at the CEDAR 25 June 2018 Santa Fe. A screen shot of one of the slides is shown in Figure 8. Some of the Swarm satellite orbit specifications presented by Stolle and the Swarm Science team by

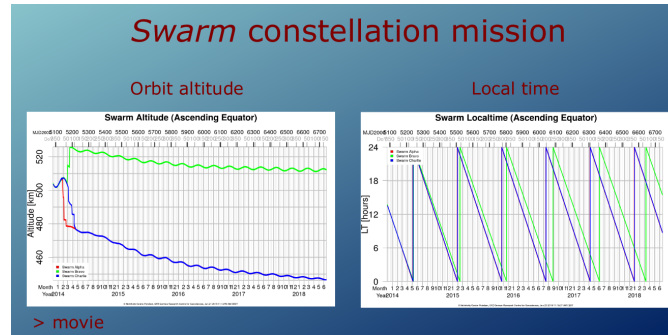


Figure 3. From Stolle and the Swarm Science Team, https://cedarweb.vsp.ucar.edu/wiki/images/d/db/2018CEDAR_Monday_Stolle2.pdf

2018 are shown in a screen shot here in Figure 10.



Figure 4. From Stolle and the Swarm Science Team, https://cedarweb.vsp.ucar.edu/wiki/images/d/db/2018CEDAR_Monday_Stolle2.pdf

Basing on the reviewer's suggestion, Figure 7 shows results of orbital analysis we carried out for the period of study (October 2014 to October 2018). Note that Figure 7 presents orbital analysis results only when the 16 Hz Ne data was available during the period of study. Figure 7 presents the evolution of the longitudinal separation between Swarm A and C, Local time of Swarm A, B, and C and time lag between Swarm spacecrafts when they passed the geographic equator during the period from October 2014 to October 2018. During the period of study, the longitudinal separation between Swarm A and C varied frequently between 1.4° and 1.46° . In general, the longitudinal separation between Swarm A and C was about 1.4° corresponding to about 160 km distance at the equator, similar to what was stated by Xiong et. al. (2016), DOI 10.1186/s40623-016-0502-5 and also presented by Stolle and the Swarm team. Figure 7(b) presents the temporal difference between Swarm A/C and B satellites from October 2014 till October 2018. From Figure 7(b), Swarm A and C cover nearly the same local time and the time lag between Swarm A and C varied frequently between 1-10 seconds (see Figure 7(c)). The local time separation

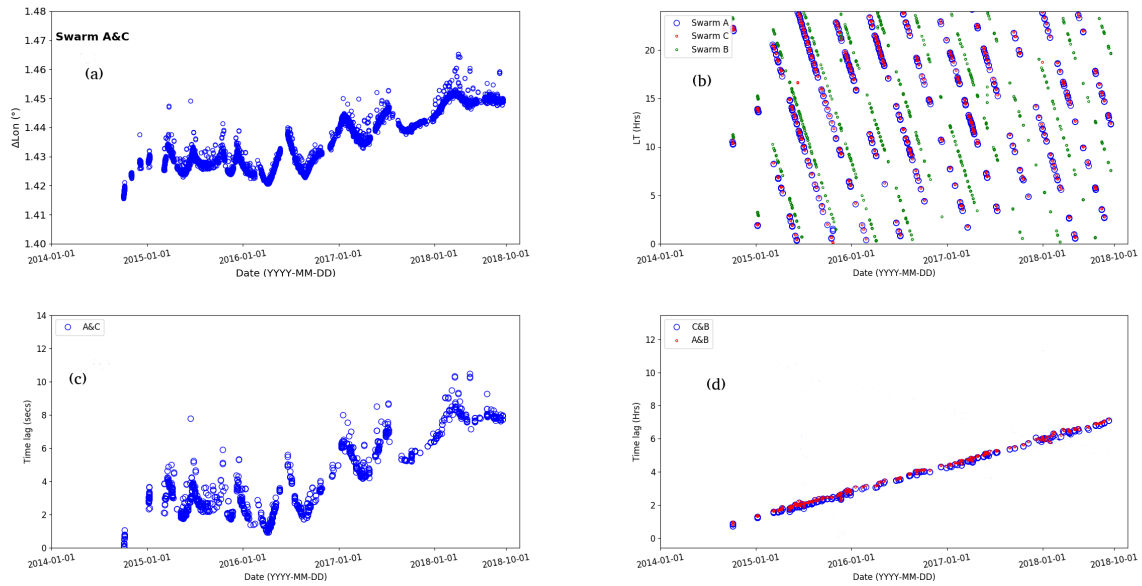


Figure 5. From Xiong et al (2016), DOI 10.1186/s40623-016-0502-5

between Swarm B and the two lower pairs is seen to increase and by October 2018, it reached up to 8 hours of time lag.

Therefore, basing on the orbit analysis results suggested by the reviewer, the sentences in Pg. 3 L. 14-20 have been updated to:

Using Swarm mission data collected from October 2014 to October 2018, orbit analysis was carried out to check on the status of the Swarm orbits. From the orbit analysis, by the end of October 2018, the longitudinal separation between Swarm A and C was about 1.4° corresponding to about 160 km distance at the equator, covering nearly the same local time sector with a time lag of about 1-10 seconds. The time lag between Swarm B and the lower pairs reached up to 8 hours. Swarm A and C were orbiting at an altitude of about 448 km altitude (orbital inclination angle of 87.35°) above sea level over the low latitude region, and Swarm B was orbiting at an altitude of about 512 km (orbital inclination angle of 87.75°).

The statement, “ ‘Swarm A and C need about 133 days to complete all 24 hours of local time and Swarm B needs about 141 days (Xiong et al., 2016b).’ has been eliminated from the revised manuscript.

3. **Comment:**P2, L25ff: The proposed detection method identifies amplitudes of deviations from a 2s-average and attribute a level of higher than $0.25 \times 10^{10} \text{m}^{-3}$ of its RMS as being an irregularity. By this method, identifying an RMS over a time window of 2 seconds (15 km), information from the 16 Hz seconds are smoothed out.

– **Response:** The window to calculate dN_e (for the case of small-scale ionospheric irregularities) should be short, but has to be long enough to avoid spurious detection of ionospheric irregularities. We also tried 1 s, 16 points, instead of 2s, 32 points, and the outcome was similar and reasonable. In addition, during the study period, the solar activity was generally low (descending phase of solar cycle 24), and ionospheric plasma perturbations were, in general, weak. Therefore, we chose a smaller threshold to capture a reasonable number of events.

4. **Comment:** Figure1/P5, L3: ‘multi-peak’ variations appropriate to the 16 Hz samples in comparison to the 2Hz samples cannot be identified in either the zoomed figures in Figure 1. Many peaks are equally visible in the 2 Hz data.

– **Response:** We present here in Figure 6 inset plots which are zoomed in further. It can now be clearly seen that multiple

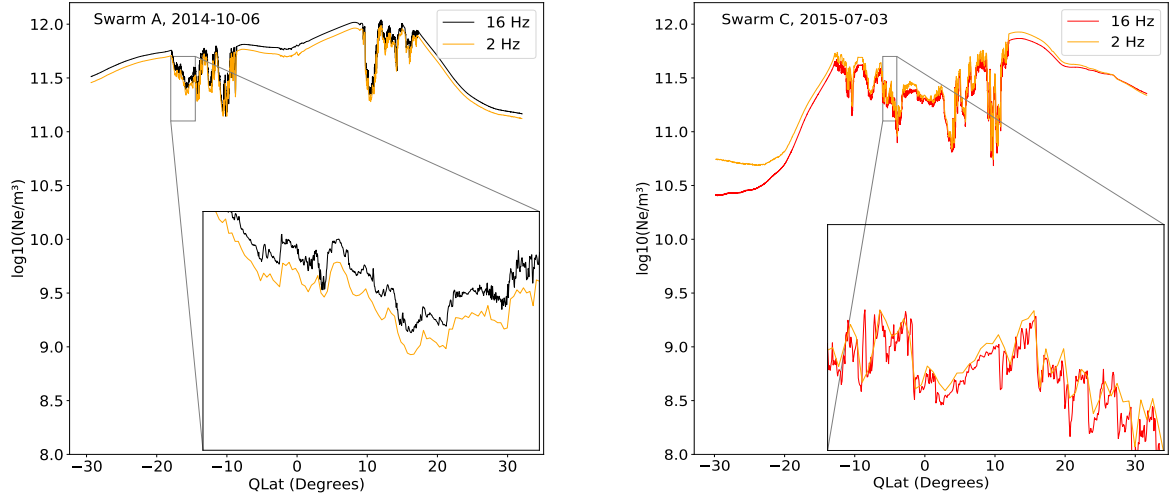


Figure 6. Comparison of 2 Hz LP data and 16 Hz faceplate data for Swarm A and C on 2014-10-06 and 2015-07-03, respectively.

electron density peaks are observed on the 16 Hz data than in the 2 Hz data. The 2 Hz data appears to be smooth and cannot show detailed small scale structures. Figure 1 in Pg. 5 in the revised manuscript has been replaced with the new zoomed in Figure.

5. **Comment:**Page 10,L9: “Large values of both ΔN_e and $\Delta N_e/N_e$ often occur in locations of large depletions in Ne.” It is not clear, where else they could be expected?

– **Response:** In the low latitudes, the values of both parameters are expected to be high in locations of plasma density depletions at the EIA crests, but also at the bottom of large scale bubbles/depletions. However, the absolute perturbation is high at the crests and at the edge of large scale bubbles/depletions. So high values of both the absolute and relative perturbations do not occur at the same place. We have shown this for the crests/equator in Figures 6, 7, and 8. To make it clear, we have rephrased the sentence to:

From Fig.2 panels (b) and (c), large values of both $\text{std}(dN_e)$ and $\text{std}(dN_e)/N_e$ often occur in locations of large depletions in N_e at the EIA crests close to the quasi-dipole equator, but also at the bottom of large scale bubbles. (see Pg. 5 L 14-15, Pg. 6 L1.)

6. **Comment:**Page 5, L15-23: The effect of relative variation compared to absolute variation was extensively discussed, e.g., for polar patches in DOI: 10.1002/2017JA024811 .

– **Response:** Chartier et al. (2018) DOI: 10.1002/2017JA024811 used N_e and Total Electron Content (TEC) measurements made by the LPs and GPS, respectively on board Swarm to test the relative and absolute perturbations in detection of polar cap patches. In the present manuscript, we extended the comparison of relative and absolute variation in the low

latitude region using the polar orbiting Swarm satellites, where the distribution of ionospheric irregularities seems to be quite different from that at the polar region. In addition, Chartier et al. (2018) used Swarm LP N_e measurements at a frequency of 2 Hz, while in the current study we used the high resolution faceplate measurements. To acknowledge the work presented by Chartier et al. 2018, DOI: 10.1002/2017JA024811, the following sentences have been added in the revised manuscript:

Chartier et al. (2018) used Ne and Total Electron Content (TEC) measurements made by the LPs and GPS, respectively on board Swarm to test the relative and absolute perturbations in detection of polar cap patches. In terms of seasonal distribution, they observed discrepancies between the two methods with relative disturbances showing more patches in winter than in summer. However, the study presented by Chartier et al. (2018) was limited to the high latitudes. (see Pg. 4 L. 1-5)

7. **Comment:**P7, L3: The authors describe that the irregularities occur between 18-06 LT, however, no other LT is shown in Figure 3.

– **Response:**The local time sector was fixed between 1800-0600 LT since over the low latitude region, ionospheric irregularities are a night time phenomena and this has been stated in the manuscript on Page 1, L. 20-21 and Page 6, L. 16-18. The reviewer is referred to Kil and Heelis, 1998; Burke et al., 2004; Su et al., 2006; Stolle et al., 2006; Dao et al., 2011; Huang et al., 2014; Xiong et al., 2016b; Wan et al., 2018 (also cited in Page 6, L. 16-18). Most of these earlier studies also limited their analysis over the low latitude region to the local time sector 1800-0600 LT. To make this clear, the statement has been rephrased to:

As mentioned earlier, ionospheric irregularities in the low latitudes are a nighttime phenomena and therefore, the analysis was restricted to the time period from 1800 LT-0600 LT. From Fig. 3, it is seen that irregularities occur from 1800 LT to 0600 LT as expected, irrespective of the method used.

(see page 6, L. 25-26, page 7, L. 1)

8. **Comment:**Figures 6,7,12 base on color scales that lie below the detection threshold by at least to 50%

– **Response:** For the climatology maps presented in Figures 6,7,12,14, all Swarm passes were considered irrespective of whether there were irregularities or not. This was done because of the limited data. However, the plots were regenerated using only Swarm passes which encountered irregularities. The results are presented in the revised manuscript. Although, less data was used after applying the defined filter, the results are reasonable and the color scales have also been updated in this regard (see Figure 6,7,12,14).

9. **Comment:**Figure 9 shows along track gradients of electron density, that are by nature directly related to ΔN_e for the detections. It is maybe not helpful to discuss their coincidence.

– **Response:** As the reviewer has mentioned, the along track gradients are indeed directly related to $\text{std}(dN_e)$. However, technically, the ∇N_e is the slope of a fitted straight line to the data, and $\text{std}(dN_e)$ is from the residuals. Both are independent, i.e. the method does not automatically imply a correlation between both. An observation of interest was that there was a slight latitudinal difference between $\text{std}(dN_e)/N_e$ and ∇N_e and therefore, it was important to include ∇N_e and compare it to $\text{std}(dN_e)/N_e$ and $\text{std}(dN_e)$. Also, from the best of our knowledge, seasonal dependence of latitudinal-longitudinal distribution of ∇N_e has not yet been presented for the case of the Swarm satellites.

10. **Comment:**Figure 12 divides below and above F10.7=140sfu. It is questionable if a significant amount of data is available for conclusions above F10.7=140sfu. See figures 10, 11 of the submission and <https://services.swpc.noaa.gov/images/solar-cycle-10-cm-radio-flux.gif>. Also, P 14 L 20ff: The authors mention similar comparisons by Huang et al., Su et al., Stolle et al. To the knowledge of the referee, these papers discussed the occurrence rate, not the amplitude of irregularities. Amplitudes are discussed by Wan et al., 2018. However, conclusion (iv) of the submitted paper mentions occurrence rates which is not compatible with Figure 12.

– **Response:**

- For the case of Fig. 12, we agree with the reviewer that the data may not have been enough after categorizing with respect to $F10.7$ especially for $140 \leq F10.7 < 180$. This limitation was also stated in the manuscript in Page 16, L 8-9 and Page 19, L 10-12. However, irrespective of the limitation in data availability, $\text{std}(dN_e)$ shows dependence on moderate solar activity similar to what was presented in earlier studies (e.g, Huang et al. (2001), Su et al. (2006), Stolle et al. (2006)) i.e, high $\text{std}(dN_e)$ values are often observed when $140 \leq F10.7 < 180$.
- As pointed out by the referee, it is true that Huang et al. (2001), Su et al. (2006), Stolle et al. (2006) did not present amplitudes of electron density perturbation, and amplitudes are discussed by Wan et al. 2018. However, Wan et al. 2018 did not present the dependence of amplitudes of ionospheric irregularities to different solar activity levels categorized in terms of $F10.7$, while the cited papers (Huang et al. (2001), Su et al. (2006), Stolle et al. (2006)) addressed the solar activity dependence of occurrence of ionospheric irregularities. A key difference between occurrence of ionospheric irregularities and their amplitudes stated by Wan et al. 2018 is that they show a totally different longitudinal pattern. The amplitudes presented in Fig. 12 seem to show similar dependence on different levels of $F10.7$ as the occurrence rates presented by Huang et al. (2001), Su et al. (2006), Stolle et al. (2006) with high $\text{std}(dN_e)$ values (or high occurrence rates) often observed when $140 \leq F10.7 < 180$. Therefore, the dependence of amplitudes, $\text{std}(dN_e)$ and occurrence rate of ionospheric ionospheric show similar dependence on solar activity level.

For clarification, the following statement has been added in the revised manuscript:

It is necessary to note that Huang et al. (2001), Su et al. (2006), Stolle et al. (2006) addressed the solar activity dependence of the occurrence rate of ionospheric irregularities. Wan et. al. 2018 presented differences between the occurrence rate of ionospheric irregularities and their amplitudes in terms of the latitudinal and longitudinal distribution. However, in general, the seasonal and longitudinal distribution of $\text{std}(dN_e)$ presented in Fig. 12 shows a similar dependence on different levels of $F10.7$ as the occurrence rates.

(see Pg. 17 L. 1-5)

- Conclusion (iv) has been rephrased considering a suggestion from Reviewer 2 Comment (5) to,

The $\text{std}(dN_e)$ showed a weak positive correlation with $F10.7$ and the correlation was even lower with $\text{std}(dN_e)/N_e$. Furthermore, $\text{std}(dN_e)$ in the EIA crest regions grew approximately linearly from the low to moderate solar activity, with higher correlation than that in the EIA trough region. The $F10.7$ dependence of the seasonal and longitudinal distribution of the ionospheric irregularities showed slightly different trends between $\text{std}(dN_e)$ and $\text{std}(dN_e)/N_e$. The discrepancy between the two methods may be because of the limited data. In general, the distribution of ionospheric irregularities was still lower during the geomagnetically disturbed period than in quiet times. Close inspection of showed that the correlation between $\text{std}(dN_e)$ and K_p was lowest at the EIA belts compared to that at the equator. The solar and magnetic activity dependence of $\text{std}(dN_e)/N_e$ hardly showed any difference in correlation between equatorial and off-equatorial latitudes.

(see Pg.20 L.26-33)

11. **Comment:** Palmroth et al., 2000 and Stolle et al., 2006 did first analyses on the relation between the occurrence rate of irregularities and the K_p index, that are not discussed in the submitted manuscript.

- **Response:** In the updated manuscript, the literature recognized by the reviewer have been integrated. (see Pg. 20 L. 11 and Pg. 19 L. 1-6)

12. **Comment:** The authors might reconsider the added value of P11 L6ff to the concerned study.

- **Response:** Concerning the difference between Swarm A/C and Swarm B, orbital analysis such as spacing between Swarm A and C, altitude difference between Swarm A/C and B, time lag between Swarm A/C and B etc was carried out in response to Comment 2.

Selected technical comment: dN_e , ΔN_e , and $(\nabla)N_e$ are used to express the same parameter.

– **Response:**

- In the revised manuscript, we have replaced ΔN_e with $\text{std}(dN_e)$ and $\text{std}(dN_e)/N_e$ to represent the absolute electron density perturbation. Also, $\Delta N_e/N_e$ has been replaced with $\text{std}(dN_e)/N_e$ to represent the relative electron density perturbation. The $\text{std}(dN_e)$ is obtained by determining the standard deviation of the residual $dN_e = N_e - \overline{N_e}$.
- ∇N_e in this manuscript represents the electron density gradient derived along the satellite tracks and it is given by: $\nabla N_e = \frac{(N_e)_f - (N_e)_i}{X_f - X_i}$, where X in this formula represents the latitude, f is the final position and i is the initial position.

Response to Reviewer 2 Comments

Comment: First of all, I would like to make some clarification according to my understanding of the manuscript. 1. The small-scale irregularities are usually embedded in the large scale irregularities (seen Figure 2 and from my experience), and they are actually the regional density fluctuation inside the plasma bubbles (PBs). 2. According to the authors' definition on the ΔN_e , that is, the standard deviation of the residuals between the original data with the mean fitting, in 32 data points (2 seconds, 0.6 degrees in latitudes, 14 Km in length). The ΔN_e quantified the density fluctuation in a spatial scale of 0.6° GLAT (normally inside a major PB), which is different from the conception of the depletion amplitudes, in my opinion.

Response:(1.) We agree with the reviewer and we are aware of this fact.(2.) We also agree that the concept of a depletion amplitude is less applicable for the small-scale amplitudes analyzed in this work, and the submitted text is not clear about this. The revision has been improved in this respect (confirm from Response to Major comments 1 and 2). As a new aspect which is possibly relevant for especially the small-scale irregularities we also analyzed the along-track gradient of Ne (as a proxy of the pressure gradient).

Major Comments

- (1) **Comment:**The author should emphasize in the article that these small-scale irregularities is not independent and has not been distinguished, from those of large-scale (PBs).

Response: The following sentence have been included in the revised manuscript,

Here, we mostly dealt with small scale ionospheric irregularities which are relevant for L-band scintillations. It is essential to note that these small-scale irregularities are not autonomous from those of large-scale ionospheric irregularities and they were not differentiated. The only satellite sampling the bottom-side, at altitudes below 300 km, has so far been the Atmosphere Explorer-E (AE-E) (Kil and Heelis, 1998). With the AE-E satellite, irregularities with relatively small amplitudes were seen without clearly developed EPBs. At altitudes above 350 km addressed by nearly all other studies smaller scale irregularities are usually embedded in EPBs. Automatic detection algorithms used in previous works do not discriminate between depletions (EPBs) and irregular multi-peak variations, with the exception of Wan et al. (2018), whose algorithm determined a depletion amplitude.

(see Pg, 4, L. 25-32).

- (2) **Comment:**Authors compared the occurrence of scintillations (quantified by ROTI) in 9 stations with the small-scale irregularities which exhibit correlations. However, as noted in previous works (e.g. Xiong et al., 2016; Wan et al., 2018), the radio signal disruption is more likely to occur when there exists PBs with large depletion amplitude. In the same reason as described in my first clarified issue, I think authors should be careful to relate the two things up.

Response:

We are aware of the fact that radio signal signal disruption is more likely to occur when there exists PBs with large depletions. We also sated in Page 2, L 11-12 that an interesting feature of these plasma irregularities is their scale sizes. They typically cover a variety of scale sizes, from a few centimeters to thousands of kilometers (Zargham and Seyler, 1989 , <https://doi.org/10.1029/ja094ia07p09009> ; Hysell and Seyler, 1998,<https://doi.org/10.1029/98ja02616>)". The bubbles themselves have horizontal sizes of order 100 km. The 9 IGS stations used in this study transmit radio signals at two L-band frequencies i.e, L1 (1575.42 MHz) and L2 (1227.60 MHz). The small-scale electron density variations commonly termed as small-scale structures are known to affect more L-band transmissions (Luhr et. al. 2014, doi: 10.3389/fphy.2014.00015, Bhattacharyya et. al. 2003, doi:10.1029/2002RS002711, Rao et. al. 2005, doi:10.1007 / s00585-997-0729-3, Spogli et. al. 2016, doi:10.1002/2016JA023222). The Swarm high resolution 16 Hz density estimates correspond to a spatial resolution of about 500 m, which is within the range of applicable Fresnel scales, and so theoretically relevant as a cause of L-band scintillations. Therefore, in the current manuscript, we compared small scale irregularity structures quantified from the Swarm 16 Hz electron density measurements with ROTI derived from VTEC measurements at L-band frequency.

Furthermore, the small scale irregularities in the equatorial topside ionosphere are mostly imbedded in EPBs, but generally they can exist independently of them. According to Kil and Heelis (1998), <https://doi.org/10.1029/97JA02698> at the bottom-side, below 300 km, small scale irregularities were frequently seen after sunset, but they rarely developed EPBs. At high latitudes small scale irregularities are often associated with polar patches which are structures of increased electron density. We acknowledge that Wan et al. (2018), <https://doi.org/10.1002/2017JA025072> developed an algorithm to determine a depletion amplitude, which should be sensitive to only EPBs. However, scintillations of radio signals would be caused by irregularities broadly near the Fresnel scale, about 500 m for the L band, and not directly by the larger scale EPB depletions. This is at least according to the well-know phase screen model. We suspect that the result of Wan et al. (2018), <https://doi.org/10.1002/2017JA025072> could be explained because deep EPBs involve steep density gradients which would create the small scale irregularities. Indeed we find a correlation between $\text{std}(dN_e)$ and the along track ∇N_e and this is presented here in Fig 7. In the equatorial F region the large amplitude EPBs are the major source of small scale irregularities

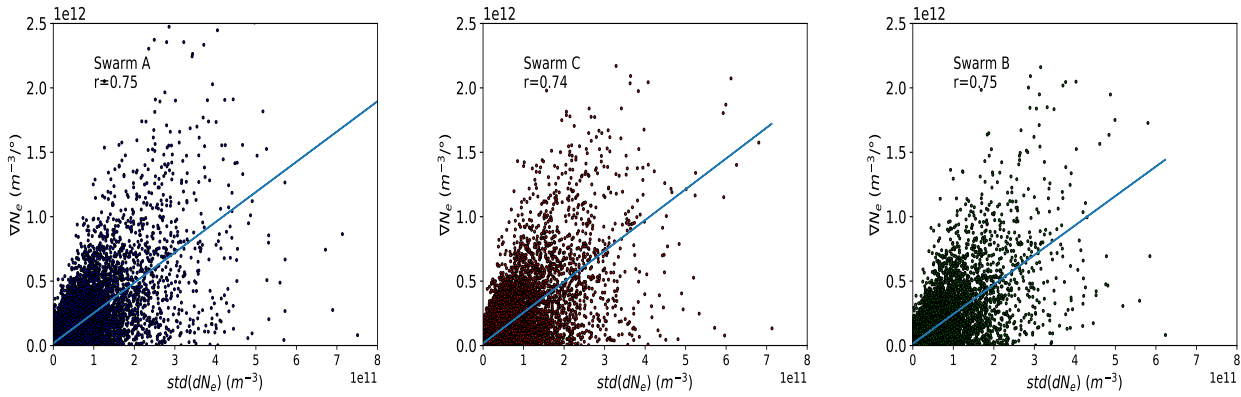


Figure 7. Correlation between $\text{std}(dN_e)$ and ∇N_e .

but not necessarily the only one. Therefore we have based our statistical analysis directly on 16 Hz (500 m scale) variations, irrespective of their creation mechanism.

- (3) **Comment:** P13 Line10 – 12: Obviously, the s/l variation of ∇N_e is similar to $\text{std}(dN_e)$ but not $\text{std}(dN_e/N_e)$, authors should describe the plots objectively.

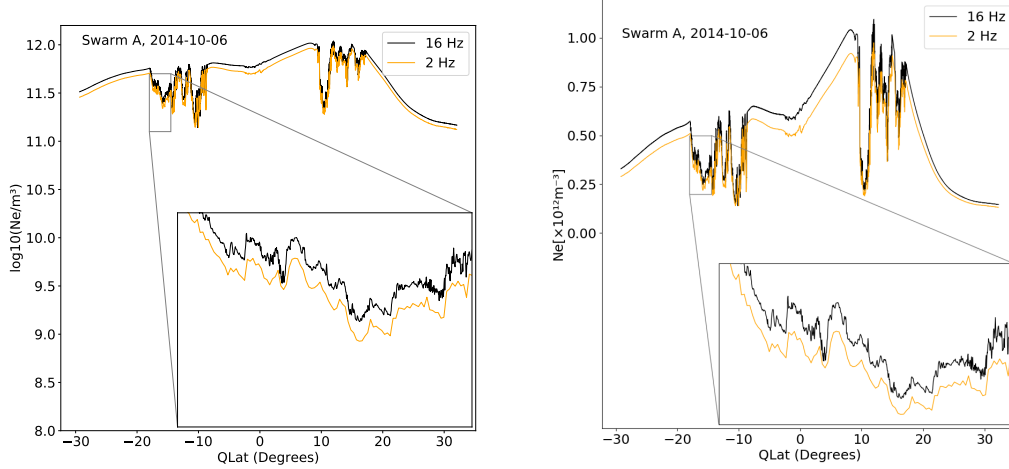
Response: The following description has been included in the manuscript in Pg. 14 L.10-15 and Pg. 15 L.1-4

The seasonal and longitudinal distribution of ∇N_e generally shows the same pattern as that of $\text{std}(dN_e)$ and $\text{std}(dN_e)/N_e$ with high values observed during the equinoxes and December solstice and moderate values in the African sector in June solstice. However, close inspection of Figure 9 shows that the ∇N_e has the same latitudinal distribution as $\text{std}(dN_e)$ i.e., it is symmetrical about the magnetic equator with high values at the EIA belts. On the other hand, the latitudinal distribution of ∇N_e is different from that of $\text{std}(dN_e/N_e)$. Earlier studies have also shown that irregularity events at latitudes of the EIA might be associated with the regions of strong density gradient (e.g, Basu et al., 2001; Keskinen et al., 2003). Therefore, the formation of small-scale irregularities appears to be more likely in ionospheric regions with higher background electron density and steep electron density gradients (Keskinen et al. 2003; Muella et al. 2008; Muella et al. 2010).

Minor comments:

(1) **Comment:**Figure 1: I would recommend the author to plot all the profiles using the absolute scale.

Response:Using the logarithmic scale makes it clearer, that the 2 Hz and 16 Hz data differ by only a nearly constant factor (which is of little relevance when analysing variations of N_e). We present here a comparison for Swarm A on 2014-10-06. As a response to a concern raised by reviewer 1 about multi-peak variations not observed in zoomed-in



section, we have zoomed in further in Figure 1 and maintained the logarithmic scale.

(2) **Comment:**P8, L19 - 20: in pre-midnight sector.

Response: In P8, L20-P9, L2, we were describing the enhanced post-midnight irregularities seen in Fig. 2(b) for June Solstice. To make it clear, the sentence has been rephrased to,

The percentage occurrence in June Solstice is generally small, comparable to that observed in Fig.2, with a broad plateau extending post-midnight. However, the enhanced post-midnight irregularities seen in Fig. 2(b) for $\text{std}(\text{d}N_e/N_e)$ in June Solstice are not observed in the LT trend of ROTI. Therefore, the LT dependence of percentage occurrence of ionospheric irregularities quantified using $\text{std}(\text{d}N_e)$ closely follows the same trend as that of ROTI for all seasons.

(see Pg. 9 L.21-22, Pg. 10 L.2)

(3) **Comment:**P8, L20 – P9, L2: It's not appropriate to explain that in a decayed sense, since the occurrence of irregularities at post-midnight is enhanced as authors found and claimed, the mechanism should be related to the lower depletion amplitudes.

Response: We do not claim that the enhanced irregularities post-midnight is related to lower depletions. The mechanisms that generate these post-midnight irregularities are still unknown and widely debated. Two mechanisms to explain post-midnight irregularity have been suggested. One mechanism is the seeding of the RTI by atmospheric gravitational waves from below into the ionosphere, while the other mechanism is the elevation of the F-layer by the thermosphere's meridional neutral winds, which may be connected with the thermosphere's highest midnight temperature. The following sentences have been included in the revised manuscript as suggested explanations for the post-midnight enhancement observed:

The mechanisms that generate these post-midnight irregularities are still unknown and widely debated. Two mechanisms to explain post-midnight irregularity have been suggested. One mechanism is the seeding of the RTI by atmospheric gravitational waves from below into the ionosphere, while the other mechanism is the elevation of the F-layer by the

thermosphere's meridional neutral winds, which may be connected with the thermosphere's highest midnight temperature (Otsuka, 2018, and references therein). (see Pg.8 L.12-13, Pg.9 L.1-2)

The statement, 'Equatorial ionospheric irregularities develop just after sunset under favorable conditions and then decay as time progresses (Kil et al., 2009).'' has been removed from the manuscript.

- (4) **Comment:**Figure 5b: It seems that the scintillation data is less available during June Solstice compared to other seasons for some stations. E.g. RIOP is totally missing. The author should mention those in the article.

Response:The following sentence has been included in the revised manuscript in Pg.9 L.16-17:

It is important to note that RIOP did not have data in June solstice and September equinox as seen in panels (b) and (c) of Fig. 5.

- (5) **Comment:** Figure 11& Figure 13: I suggest the authors do the correlation analysis regards to different latitudinal bins (i.e. equator and off-equator).

Response:We agree with the reviewer that the geomagnetic and solar activity dependence of occurrence of ionospheric irregularities at different latitudinal regions (i.e, equator and off-equator) would be interesting to know.

- Previously, Liu et. al. 2007, JGR,112, A11311, doi:10.1029/2007JA012616 investigated the solar activity dependence of the electron density at equatorial and low latitudes. We present here a snapshot of one of the results extracted from Liu et. al. 2007 concerning latitudinal distribution on solar activity dependence of electron density. From the results presented by Liu et. al. 2007, the electron density in the crest regions of the EIA grows roughly

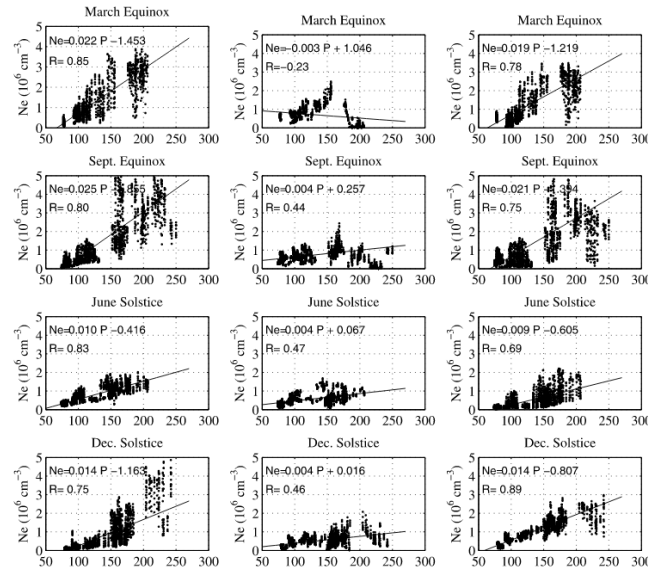


Figure 8. Same as Figure 7 but for postsunset (1800–2300 MLT) sector for the (left) northern EIA crest, (middle) dip equator, and (right) southern EIA crest.

linearly from solar minimum to solar maximum, with higher growth rate than in the EIA trough region. However, Liu et. al. 2007 did not quantify ionospheric irregularities in their analysis. Therefore, we attempted the suggestion made by the reviewer.

- The Swarm satellite passes were divided into three latitudinal ranges i.e, Equator ($\pm 5^\circ$ quasi-dipole latitude), Southern EIA region (-30° – -5° quasi-dipole latitude), and Northern EIA region ($+5^\circ$ – $+30^\circ$ quasi-dipole latitude). A summary of the latitudinal ranges is presented in a map in Figure 8.

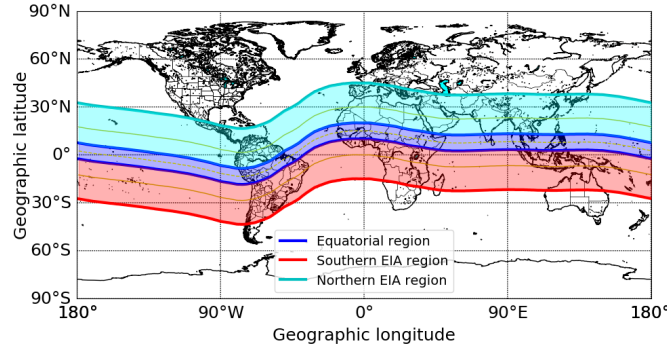


Figure 8. A summary of the latitudinal ranges

Scatter plots of (a) $\text{std}(dN_e)$ and (b) $\text{std}(dN_e)/N_e$ as functions of F10.7 are shown in Fig. 9 for Swarm A, B, and C, independently. The correlation is generally low irrespective of the latitudinal region and this may be attributed to the small data sample. However, it can be seen that the correlation between F10.7 and $\text{std}(dN_e)$ is higher at the EIA regions than at the equator. This shows also the symmetrical distribution of $\text{std}(dN_e)$ with high values obtained at the EIA belts than at the equator as seen in Fig. 6 in the manuscript. On the other hand $\text{std}(dN_e)/N_e$ hardly shows any significant difference in correlation with F10.7 at the equator and at the EIA belts. For the case of $\text{std}(dN_e)$ dependence on Kp as presented in Fig. 10, it is a generally weak correlation and it is more negative at the equator than off equatorial latitudes. For $\text{std}(dN_e)/N_e$, the correlation is very weak with both Kp and F10.7. There is hardly any difference observed between equatorial and off equatorial latitudes. The results obtained for $\text{std}(dN_e)$ is consistent with that of Liu et. al. 2007, but $\text{std}(dN_e)/N_e$ shows discrepancies with the results of Liu et al 2007.

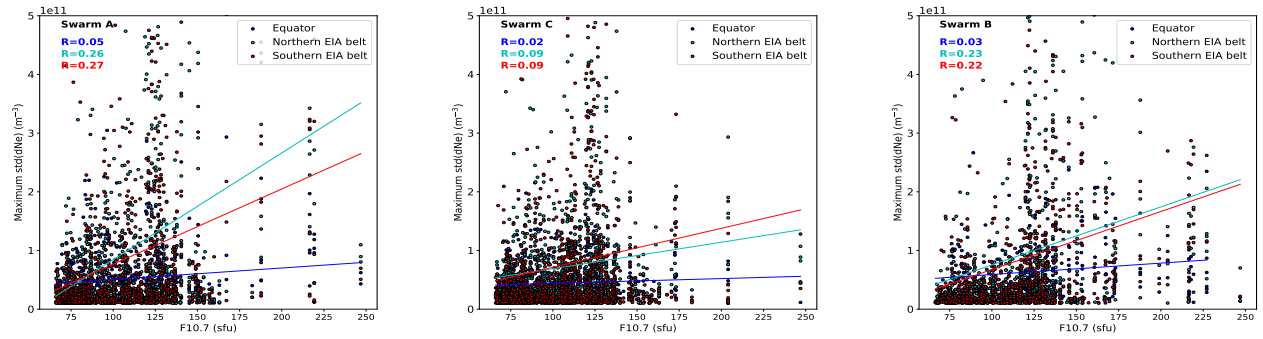
- The reviewers suggestion has been considered in the revised manuscript and Fig 11 and 13 in the manuscript have been replace with Fig 2 and Fig 3. Also the following descriptions have been incorporated in the manuscript:

To check on the solar activity dependence of $\text{std}(dN_e)$ and $\text{std}(dN_e)/N_e$ at the equator and the EIA belts, the Swarm satellite passes were divided into three latitudinal ranges i.e, Equator ($\pm 5^\circ$ quasi-dipole latitude), Southern EIA region ($-30^\circ - -5^\circ$ quasi-dipole latitude), and Northern EIA region ($+5^\circ - +30^\circ$ quasi-dipole latitude) (see legend of Fig. 11). Each panel of Fig. 11 contains linear fits and the correlation coefficients R . In general, both $\text{std}(dN_e)$ and $\text{std}(dN_e)/N_e$ show weak positive correlation with F10.7 irrespective of the latitudinal range and this may be attributed to the small data-set used. However, it can be seen that the correlation between F10.7 and $\text{std}(dN_e)$ is higher at the EIA regions than at the equator. This also shows the symmetrical distribution of $\text{std}(dN_e)$ with high values obtained at the EIA belts than at the equator. There is hardly any difference observed between equatorial and off equatorial latitudes for the case of $\text{std}(dN_e)/N_e$. The results obtained for $\text{std}(dN_e)$ is consistent with that of Liu et al (2007) who presented the solar activity dependence of the electron density in the equatorial anomaly regions.(see Pg 15 L. 18-23, Pg 16 L. 1-4)

To generate Fig. 13, the Swarm passes were also split into equatorial and EIA latitudes, similar to Fig. 11. (see Pg 17 L. 10-11)

Close inspection of Fig. 13 shows that the correlation between $\text{std}(dN_e)$ and Kp was lowest at the EIA belts compared to that at the equator. There is hardly any difference observed between equatorial and off equatorial latitudes for the case of $\text{std}(dN_e)/N_e$. Dao et al. (2011) adopted the relative perturbation to quantify irregularities. Their reason for using the relative perturbation was that the absolute perturbation is correlated with the ambient ion density, which varies due to several factors such as varying altitude. The results shown in Fig. 11 and 13 also show that $\text{std}(dN_e)$ is more sensitive to solar and magnetic variations compared to $\text{std}(dN_e)/N_e$. The differences in the correlation between F10.7 or Kp and $\text{std}(dN_e)$ or $\text{std}(dN_e)/N_e$ at equatorial and off-

(a) $\text{std}(dN_e)$



(a) $\text{std}(dN_e)/N_e$

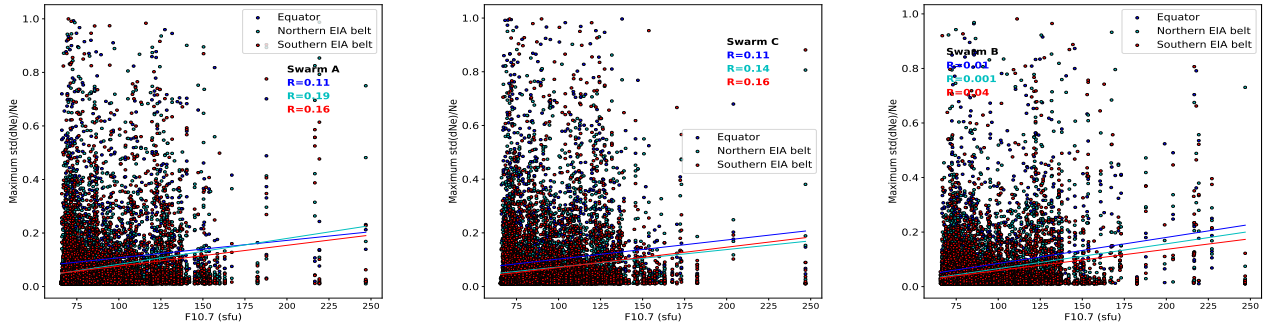


Figure 9. The distribution characteristics of (a) $\text{std}(dN_e)$ and (b) $\text{std}(dN_e)/N_e$ with respect to 10.7 cm solar radio flux in solar flux units for the period from October 2014 to October 2018.

equatorial latitudes can be explained by the differences in background electron density and electron density gradients at the crests and trough.(see Pg 17 L. 13-14 and Pg 18, L. 5-6)

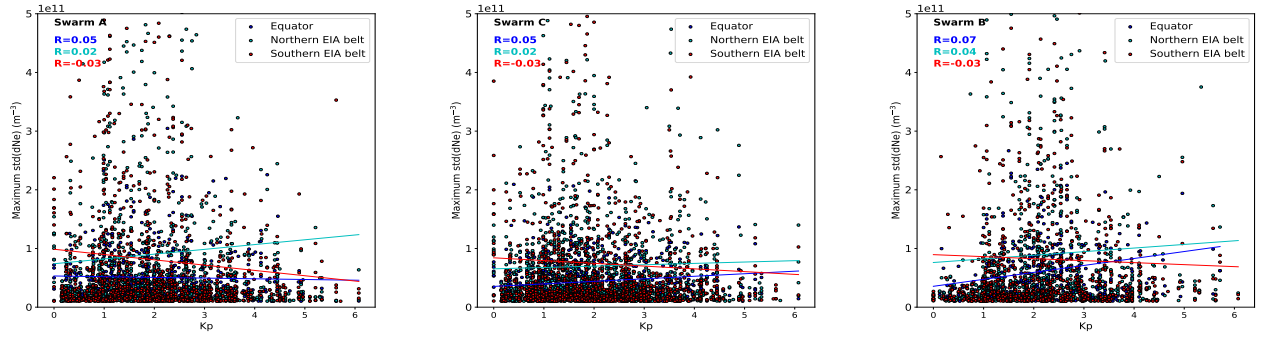
Conclusion (iv) has also been re-written to:

The $\text{std}(dN_e)$ showed a weak positive correlation with $F10.7$ and the correlation was even lower with $\text{std}(dN_e)/N_e$. Furthermore, $\text{std}(dN_e)$ in the EIA crest regions grew approximately linearly from the low to moderate solar activity, with higher correlation than that in the EIA trough region. The $F10.7$ dependence of the seasonal and longitudinal distribution of the ionospheric irregularities showed slightly different trends between $\text{std}(dN_e)$ and $\text{std}(dN_e)/N_e$. The discrepancy between the two methods may be because of the limited data. In general, the distribution of ionospheric irregularities was still lower during the geomagnetically disturbed period than in quiet times. The correlation between $\text{std}(dN_e)$ and K_p was lowest at the EIA belts compared to that at the equator. The solar and magnetic activity dependence of $\text{std}(dN_e)/N_e$ hardly showed any difference in correlation between equatorial and off-equatorial latitudes.(see Pg. 20 L.26-33)

L13-16 of the abstract has also been rephrased to:

The reliance of $\text{std}(dN_e)/N_e$ on solar and magnetic activity showed little distinction in the correlation between equatorial and off-equatorial latitudes, whereas $\text{std}(dN_e)$ showed significant differences. With regard to

(a) $\text{std}(dN_e)$



(a) $\text{std}(dN_e)/N_e$

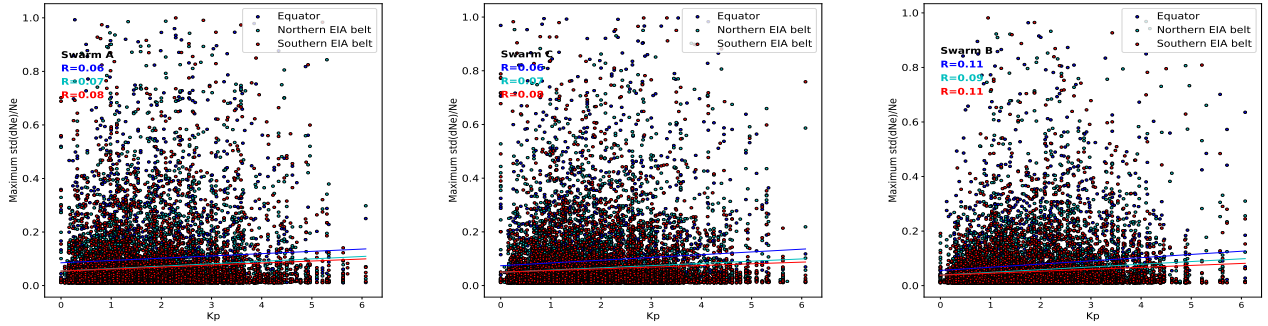


Figure 10. The distribution characteristics of (a) $\text{std}(dN_e)$ and (b) $\text{std}(dN_e)/N_e$ with respect to K_p for the period from October 2014 to October 2018.

seasonal and longitudinal distribution, high $\text{std}(dN_e)$ and $\text{std}(dN_e)/N_e$ values were often found during quiet magnetic periods compared to magnetically disturbed periods. The $\text{std}(dN_e)$ increased approximately linearly from low to moderate solar activity.

(6) **Comment:**P13 Line 12, Linking word is missing.

Response:The statements have been rephrased in the revised manuscript to,

The formation of small-scale irregularities appears to be more likely in ionospheric regions with higher background electron density and steep electron density gradients (Keskinen et al., 2003; Muella et al., 2008; Muella et al., 2010). Therefore, the amplitudes of ionospheric irregularities closely depend on background electron density (Wan et al., 2018) and steep N_e gradient globally as expected.

(see lines Pg. 15 L.1-4)

(7) **Comment:**P17, Line 11-12: It is not an accurate description.

Response:This has been rephrased to,

The $\text{std}(dN_e)/N_e$ showed a peak at the quasi-dipole equator which gradually decreased towards higher latitudes. in the revised manuscript. (see Pg.20 L.20-21)

(8) **Comment:**In many, authors inappropriately describe the ΔN_e but not $\Delta N_e/N_e$ as the ‘irregularities’ (e.g. the captions of Figure 13, 14).

Response:The captions of Fig.13 and Fig. 14 have been rephrased to ,

The distribution characteristics of (a) $\text{std}(dN_e)$ and (a) $\text{std}(dN_e)/N_e$ with respect to Kp index for the period from October 2014 to October 2018. The black lines in each panel represent a linear fit to the data.

Geomagnetic effect on seasonal and longitudinal distribution of $\text{std}(dN_e)$ and $\text{std}(dN_e)/N_e$ for the period from October 2014 to October 2018: A case for Swarm A.,

respectively in the revised manuscript.

Response to Reviewer 3 Comments

In this paper, the ionospheric irregularities are studied by using two methods: the absolute and relative changes of electron density. The distribution characteristics with local time, season and longitude of irregular structures are reproduced. The differences in the latitudinal distribution, and the correlation difference with F107 between the two methods are reported. The main problem for the reviewer is that the relative change depends on both the absolute change in electron density and the value of background electron density. The strong relative change in the equatorial region may be due to the weaker background electron density. The dependence on F107 is not strong and may also be due to changes in background electron density with F107. From this point of view, perhaps absolute changes may be more suitable for studying the ionospheric irregularities. So I don't know why the author should use the relative change as a way to study the ionospheric irregularities? I hope they can explain why. More interesting is the finding of the importance of the meridional difference in electron density in the irregular structure of the ionosphere. Could they explain more about the physical mechanism?

Response:

- We are aware of the fact that the relative change depends on both the absolute change in electron density and the value of the background electron density. We are also aware that the strong relative change in the equatorial region may be due to the weaker background electron density. We also mentioned in the manuscript in Pg. 14 L. 3-5 that, "From both local time and longitudinal perspectives, Wan et al. (2018), <https://doi.org/10.1002/2017JA025072> confirmed that the depletion amplitudes of irregularities are closely linked to the background electron density intensity." From the results obtained by Wan et al. (2018), <https://doi.org/10.1002/2017JA025072> it is observed that high background electron density is concentrated at the EIA belts than at the magnetic equator. We also mentioned in Pg. 14 L.1-3 that, "Among other parameters, the growth rate of equatorial ionospheric irregularities is controlled by the electron density gradient. Ionospheric irregularities in the equatorial and low latitudes can cascade upwards and along the magnetic field lines to the EIA belts characterized by high background N_e and steep gradients in density (Muella et al., 2010)."
- The question asked by the reviewer i.e, why we use the relative change as a way to study the ionospheric irregularities, is one of the motivations for the current manuscript. Multiple studies have adopted the relative change to quantify ionospheric irregularities, while others have adopted the absolute perturbation (The reviewer is referred to the literature cited in Pg.3 L.25-26). Dao et. al. (2011), doi:10.1029/2011GL047046 adopted the relative perturbation to quantify irregularities. Their reason for using the relative perturbation was that the absolute perturbation is correlated with the ambient ion density, which varies due to several factors such as varying altitude. Instead, they computed the normalized depletion of ambient density, $\Delta N/N$, in an attempt to decouple any variables associated with the varying ambient density.

However, discrepancies between the two methods in terms of identifying ionospheric irregularities have also been identified in earlier studies (This has been discussed in Pg. 3 L. 28-33, Pg. 4 L. 1-5). In Pg.3 L. 28-33, we also explain how comparison of the two methods is important in the meridional direction. Therefore, in this manuscript we use the relative change as a way to identify ionospheric irregularities to compare with absolute change.

The absolute changes are most relevant to assess the effects of irregularities on radio signals and scintillations, which is for applied purposes. However, for studying the physical mechanisms causing irregularities the relative change is perhaps more important. For example, if a plasma instability is suspected to be the cause of irregularities, the observed relative change can give indications whether the disturbances can be assumed linear (small relative changes up to perhaps 10 %) or non-linearity needs to be considered (larger relative changes). Therefore, we think that it makes sense to investigate the statistical occurrences of both absolute and relative changes.

- Concerning the mechanism responsible for the meridional distribution of ionospheric irregularities,
 - Ionospheric irregularities are generated after sunset in the low latitude region due to the plasma instabilities and the most important parameter for their development is the equatorial evening vertical plasma drift ($\mathbf{E} \times \mathbf{B}/B^2$) (Fejer et al, 1999, <https://doi.org/10.1029/1999JA900271>, Abdu 2005, DOI: 10.1016/j.asr.2005.03.150)

known as the pre-reversal enhancement in vertical drift when the eastward electric field is intensified due to the action of the F region dynamo. At low latitudes, the ionosphere presents the EIA with high electron density observed between about $\pm 15^\circ - \pm 20^\circ$ magnetic latitude. The EIA have their origin in the upward $\mathbf{E} \times \mathbf{B}$ plasma drift of the equatorial F layer. The zonal electric field that exists in the equatorial ionosphere is

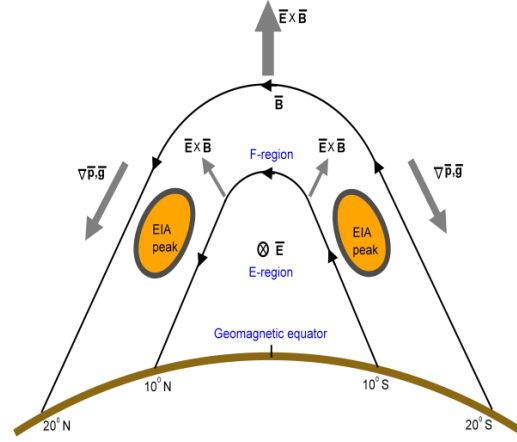


Figure 11. Appleton Anomaly Scheme

directed to the east during day, creating an upward vertical $\mathbf{E} \times \mathbf{B}/B^2$ drift velocity. Soon after the sunset, this eastward electric field is intensified (pre-reversal peak) by the F region dynamo and the plasma from F region is uplifted to high altitudes. Meanwhile, the plasma from low altitudes quickly decline due to the decreasing of the intensity of incident solar radiation (Kelley, 2009). After lifting to high altitudes in the equatorial region, the plasma starts a descent movement along magnetic field lines. This movement happens due to the action of gravity (g) and pressure gradient (∇p) forces as illustrated in Figure 11. This phenomenon (the plasma elevation and the subsequent descent along magnetic field lines to low latitudes) is known as the fountain effect, giving origin to the EIA. The upward vertical plasma drift in the equator after sunset that gives origin to the pre-reversal peak, is the main factor responsible for the plasma irregularity generation (Fejer et al., 1999, <https://doi.org/10.1029/1999JA900271>). This means that around sunset at low latitudes, the enhanced eastward electric field in F region enlarges the equatorial fountain effect, causing the two crests of the EIA to get stronger and the trough above the dip equator to become deeper. We also quoted in Pg 12 L.10-11 that, “Ionospheric irregularities in the equatorial and low latitudes can cascade upwards and along the magnetic field lines to the EIA belts characterized by high background N_e and steep gradients in density (Muella et al., 2010, <https://doi.org/10.1029/2009JA014788>).”

- The difference in latitudinal distribution of ionospheric irregularities as observed in the meridional direction characterized by $\text{std}(dN_e)$ and $\text{std}(dN_e)/N_e$ as discussed in the manuscript can be explained by the differences in background electron density and electron density gradients at the crests and trough. As mentioned by the reviewer, high values of $\text{std}(dN_e)/N_e$ occur at the equator because it depends on the background electron density which is low at the magnetic equator. High values of $\text{std}(dN_e)$ occur at the crests because of high background electron density at these locations and steep electron density gradients (as presented in Figure 9).

Traits of sub-kilometer F-region irregularities as seen with the Swarm satellites

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Abstract. During the night, in the F-region, equatorial ionospheric irregularities manifest as plasma depletions observed by satellites and they may cause radio signals to fluctuate. In this study, the distribution characteristics of ionospheric F-region irregularities in the low latitudes were investigated using 16 Hz electron density observations made by the faceplate on board Swarm satellites of the European Space Agency (ESA). The study covers the period from October 2014 to October 2018 when the 16 Hz electron density data were available. For comparison, both the absolute ($\text{std}(dN_e)$) and relative ($\text{std}(dN_e)/N_e$) density perturbations were used to quantify the level of ionospheric irregularities. The two methods generally reproduced the local time, seasonal and longitudinal distribution of equatorial ionospheric irregularities as shown in earlier studies, demonstrating the ability of Swarm 16 Hz electron density data. A difference between the two methods was observed based on the latitudinal distribution of ionospheric irregularities where $\text{std}(dN_e)$ showed a symmetrical distribution about the magnetic equator, while $\text{std}(dN_e)/N_e$ showed a magnetic equator centered Gaussian distribution. High values of $\text{std}(dN_e)$ and $\text{std}(dN_e)/N_e$ were observed in spatial bins with steep gradients of electron density from a longitudinal and seasonal perspective. The response of ionospheric irregularities to geomagnetic and solar activities was also investigated using Kp index and solar radio flux index (F10.7), respectively. The reliance of $\text{std}(dN_e)/N_e$ on solar and magnetic activity showed little distinction in the correlation between equatorial and off-equatorial latitudes, whereas $\text{std}(dN_e)$ showed significant differences. With regard to seasonal and longitudinal distribution, high $\text{std}(dN_e)$ and $\text{std}(dN_e)/N_e$ values were often found during quiet magnetic periods compared to magnetically disturbed periods. The $\text{std}(dN_e)$ increased approximately linearly from low to moderate solar activity. Using the high-resolution faceplate data, we were able to identify ionospheric irregularities of scales of only a few hundreds of meters.

Keywords. Low latitude ionosphere, Ionospheric irregularities, seasonal and longitudinal climatology

1 Introduction

Noticeable features in the low-latitude ionosphere are plasma density irregularities which occur after sunset in the F-region (Kil and Heelis, 1998). They may be identified as density decrease along satellite passes referred to as Equatorial Plasma Bubbles (EPBs) or range and frequency spread signatures on ionograms commonly called Equatorial Spread F (ESF) (Woodman and La Hoz, 1976; Burke et al., 2004). The generalized Rayleigh Taylor Instability (RTI) is the suggested mechanism which can explain how ionospheric irregularities occur in the low latitudes (Woodman and La Hoz, 1976; Gentile et al., 2006; Portillo

et al., 2008; Nishioka et al., 2008; Kelley, 2009; Schunk and Nagy, 2009). They may cause disruptions in trans-ionospheric radio signals of frequencies ranging from a few hundred kilohertz to several gigahertz, which in turn degrade the performance of communication and navigation systems (Kil and Heelis, 1998; Kintner et al., 2007).

There are many studies on the distribution characteristics of equatorial ionospheric irregularities (e.g., Kil and Heelis, 1998; Huang et al., 2002; Burke et al., 2004; Makela et al., 2004; Park et al., 2005; Su et al., 2006; Stolle et al., 2006; Kil et al., 2009; Dao et al., 2011; Xiong et al., 2012; Carter et al., 2013; Huang et al., 2014; Costa et al., 2014). Long-term observations of equatorial ionospheric irregularities have shown that their occurrence depends on various geophysical parameters including longitude, latitude, altitude, local time, season, solar activity and geomagnetic conditions (Kil et al., 2009). The dependence of ionospheric irregularities on the geophysical parameters, however, remains a problem in modeling their variation for predictive purposes (Yizengaw and Groves, 2018). Therefore, further global-scale studies on the distribution characteristics of ionospheric irregularities and their dependence on various factors are still necessary. An interesting feature of these plasma irregularities is their scale sizes. They typically cover a variety of scale sizes, from a few centimeters to thousands of kilometers (Zargham and Seyler, 1989; Hysell and Seyler, 1998). The meter scales correspond to radio waves at HF and VHF frequencies where irregularities are associated with Bragg scattering of radio waves and the spread F phenomenon (Woodman, 2009). The in situ measurements by satellites are normally suitable for analyzing the global aspects of the statistics of ionospheric irregularities. Depending on the sampling rate, spatial scales from about 100 m and larger can be seen. However, the orbital characteristics of satellite missions can limit the statistical coverage regarding altitude, latitude, local time, solar cycle phase, seasons, longitude, and aspect angle with respect to the geomagnetic field. Stolle et al. (2006) used magnetic observations made by the polar-orbiting CHALLENGING Minisatellite Payload (CHAMP) satellite for the years 2001 – 2004 to study the irregularities. Multi-peak electron density fluctuations were not observed in the results presented by Stolle et al. (2006) due to the low sampling rate of the Planar Langmuir Probe (PLP) measurements. However, the CHAMP satellite's magnetic field data recorded at a frequency of 50 Hz showed irregularity structures as small as 50 m in scale size (Stolle et al., 2006). Multiple studies have also used high-resolution data sets when available to check the distribution characteristics of ionospheric irregularities and have been able to resolve plasma density structures to smaller scales along satellite tracks (e.g. Lühr et al., 2014; Huang et al., 2014, etc).

The Launch of the first Earth observation constellation mission of the European Space Agency (ESA), i.e., Swarm, in November 22, 2013, generated new interests in the study of ionospheric irregularities. A number of studies have demonstrated the use of Swarm satellites for observations of ionospheric irregularities (e.g. Buchert et al., 2015; Zakharenkova et al., 2016; Xiong et al., 2016; Xiong et al., 2016b; Wan et al., 2018; Yizengaw and Groves, 2018; Jin et al., 2019; Kil et al., 2019, etc). Most of these studies have used electron density measurements at a frequency of 2 Hz or 1 Hz made by the Langmuir Probes (LPs) on-board Swarm. Xiong et al. (2016) used Swarm 2-Hz electron density measurements to check the scale sizes of irregularity structures. They suggested that the structures have scale sizes in the zonal direction less than 44 km. The Swarm satellites have the capability of measuring electron density at an even higher frequency of 16 Hz using a faceplate. Swarm can record ionospheric irregularities of scale lengths up to 500 m along their tracks using the 16 Hz electron density measurements. High-resolution data enables smaller scale structures to be identified in electron density (Nishioka et al., 2011). The 16 Hz electron density data from Swarm satellite has not yet been used to study traits of ionospheric irregularities. In the present

study, we looked at the distribution characteristics of equatorial ionospheric irregularities using 16 Hz faceplate measurements of electron density. The study covers the period from October 2014 to October 2018 corresponding to the descending phase of solar cycle 24, when the 16 Hz electron density data was available. We show that the electron density measurements of Swarm faceplate can be applied to examine the characteristics of ionospheric equatorial irregularities at sub - kilometers scale lengths.

5 The rest of the paper is organized in the following order: The data and methods are presented in Sect. 2. The results are presented and discussed in Sect. 3. The summary and conclusions are presented in Sect. 4.

2 Data and Methods

The Swarm mission is made up of three same satellites (Swarm A, B, and C) with an orbital speed of around 7.5 km s^{-1} in polar orbits. Each satellite is equipped with an Electric Field Instrument (EFI) in addition to other payloads. The EFI consists of LPs, and Thermal Ion Imagers (TII) (Knudsen et al., 2017). The LPs measure simultaneously the electron density (N_e), electron temperature (T_e), and spacecraft potential at a frequency of 2 Hz along the satellites' track. The Swarm satellites also measure N_e at a frequency of 16 Hz with a faceplate only when the TII is inactive. The Plasma density 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). Knudsen et al. (2017) provide more details on how electron density is derived from the LPs and TII. Using Swarm mission data collected from October 2014 to October 2018, orbit analysis was carried out to check on the status of the Swarm orbits. From the orbit analysis, by the end of October 2018, the longitudinal separation between Swarm A and C was about 1.4° corresponding to about 160 km distance at the equator, covering nearly the same local time sector with a time lag of about 1-10 seconds. The time lag between Swarm B and the lower pairs reached up to 8 hours. Swarm A and C were orbiting at an altitude of about 448 km altitude (orbital inclination angle of 87.35°) above sea level over the low latitude region, and Swarm B was orbiting at an altitude of about 512 km (orbital inclination angle of 87.75°). In a day, the swarm satellites complete about 16 orbits with an average orbital period of about 91.5 min. Swarm satellites regress in longitude around 22.5° between orbital ascending nodes. Data sets measured by Swarm can be downloaded from <http://earth.esa.int/swarm>. The investigations done in this study are based on the 16 Hz N_e faceplate data collected for the period of October 2014 to October 2018.

25 The identification criteria adopted for quantifying ionospheric irregularities have been a matter of concern. Some earlier studies (e.g, Kil and Heelis, 1998; McClure et al., 1998; Burke et al., 2003; Su et al., 2006; Kil et al., 2009; Dao et al., 2011, etc) used relative plasma density disturbance to identify ionospheric irregularities while others (e.g, Lühr et al., 2014; Buchert et al., 2015; Xiong et al., 2016b, etc) took absolute density disturbance. However, Huang et al. (2014) used the 512 Hz Communication / Navigation Outage Forecasting System (C / NOFS) satellite's measurements of ion density and found that when the relative and absolute density disturbances are used independently, the likelihood of irregularities occurring and their variation with local time differ. The C / NOFS satellite was in a low tilt orbit, so the bubbles were sampled zonally. Important differences basing on latitudinal distribution of ionospheric irregularities using different criteria could not be addressed by Huang et al. (2014). The polar-orbiting Swarm satellites sample bubbles in a meridional direction and they give an opportunity

to check the difference in the latitudinal distribution of irregularities using different identification criteria. Chartier et al. (2018) used N_e and Total Electron Content (TEC) measurements made by the LPs and GPS, respectively on board Swarm to test the relative and absolute perturbations in the detection of polar cap patches. In terms of seasonal distribution, they observed discrepancies between the two methods with relative disturbances showing more patches in winter than in summer. However, the study presented by Chartier et al. (2018) were limited to high latitudes.

For comparison purposes, two methods were also adopted for the polar-orbiting Swarm satellites to quantify the level of electron density irregularities in the low latitude region. In the first method, the 16 Hz N_e measurements were passed through a 2-s (32 data points) running mean filter corresponding to a wavelength of about 15 km. From the original observations, the filtered data were subtracted to obtain the residual $dN_e = N_e - \bar{N}_e$; where \bar{N}_e is the mean of N_e at a 2-s interval. The standard deviation of the residuals which represents the density perturbation, $\text{std}(dN_e)$ was then calculated for every 32 data points. Basu et al. (1976) found that, on a global scale, absolute density perturbation equal to $1 \times 10^{-10} \text{ m}^{-3}$ represents the percentage occurrence of 140 MHz scintillations. Xiong et al. (2010) used absolute density disturbance thresholds of $5 \times 10^{10} \text{ m}^{-3}$ and $3 \times 10^{10} \text{ m}^{-3}$ respectively to identify density irregularity structures on CHAMP and GRACE observations. Wan et al. (2018) adopted absolute density perturbation $> 5 \times 10^{10} \text{ m}^{-3}$ to identify ionospheric irregularities from Swarm. Basing on the method used in the current study, only batches with $\text{std}(dN_e)$ greater than $0.25 \times 10^{10} \text{ m}^{-3}$ were considered to be significantly irregular and selected for extra processing and analysis. In the second method, $\text{std}(dN_e)$ was divided by \bar{N}_e to obtain the relative perturbation, $\text{std}(dN_e)/N_e$. There is no specific threshold definition to be used when $\text{std}(dN_e)/N_e$ identifies irregularities (Huang et al., 2014; Wan et al., 2018). Kil and Heelis (1998) determined the likelihood of occurrence of relative disturbance $> 1\%(0.01)$ and $5\%(0.05)$ from Atmospheric Explorer-E (AE - E) satellite data. The AE - E satellite data was also used by McClure et al. (1998), but relative disturbances $> 0.5\%(0.005)$ were used to identify irregularities. To identify the occurrence of ROCSAT-1 irregularities, Su et al. (2006) and Kil et al. (2009) used a threshold of $0.3\%(0.003)$ for the relative disturbance. Huang et al. (2014) used high-resolution ion density measurements from the C / NOFS satellite and took relative perturbation $> 1\%(0.01)$. Wan et al. (2018) considered relative perturbation values larger than 20%. In the current study, only batches with $\text{std}(dN_e)/N_e > 0.01$ were considered to be significantly irregular and used for further analysis basing on the methods adopted. Here, we mostly dealt with small scale ionospheric irregularities which are relevant for L-band scintillations. It is essential to note that these small-scale irregularities are not autonomous from those of large-scale ionospheric irregularities and they were not differentiated. The only satellite sampling the bottom-side, at altitudes below 300 km, has so far been the Atmosphere Explorer-E (AE-E) (Kil and Heelis, 1998). With the AE-E satellite, irregularities with relatively small amplitudes were seen without clearly developed EPBs. At altitudes above 350 km addressed by nearly all other studies, smaller scale irregularities are usually embedded in EPBs. Automatic detection algorithms used in previous works do not discriminate between depletions (EPBs) and irregular multi-peak variations, with the exception of Wan et al. (2018), whose algorithm determined a depletion amplitude. The results are presented and discussed in the following section.

3 Results and Discussions

The high-resolution Swarm faceplate N_e data were used to characterize ionospheric irregularities using procedures described in Sect. 2. Figure 12 shows examples of N_e results for arbitrary passes of Swarm A and C on 2014-10-06 and 2015-07-03,

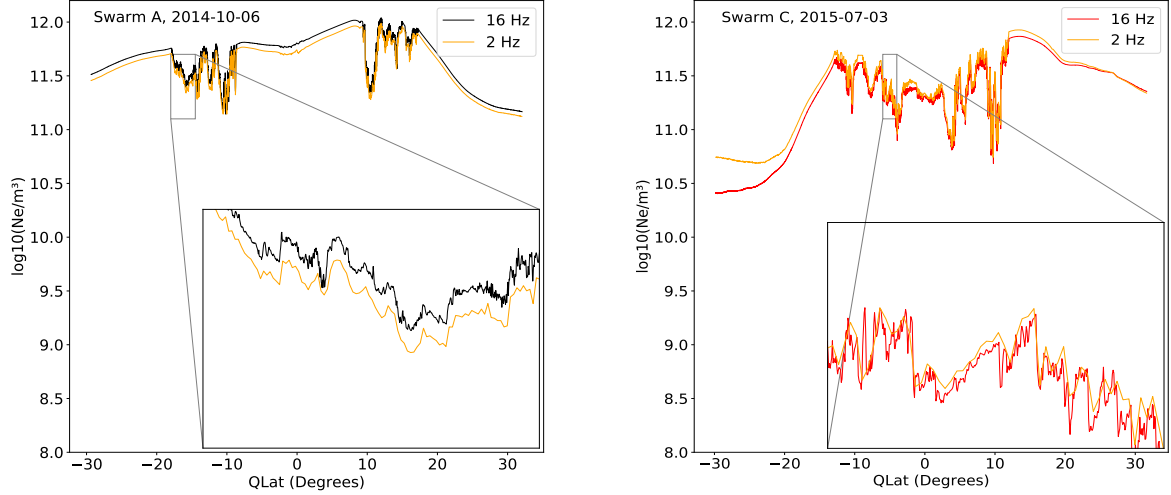


Figure 12. Comparison of 2 Hz LP data and 16 Hz faceplate data for Swarm A and C on 2014-10-06 and 2015-07-03, respectively.

respectively from the LP and faceplate to highlight the capability of the 16 Hz N_e data for observations of irregularity density structures. In Fig. 12, the orange curve is the time series of the 2 Hz LP data, while the black and red curves are the time series of the 16 Hz faceplate data for Swarm A and C, respectively. Both the 16 Hz and 2 Hz N_e data show large density depletion along the satellite tracks concentrated at about $\pm 15^\circ$ quasi-dipole latitude (QLat). The 16 Hz N_e data were able to capture fluctuations in N_e just as the 2 Hz data. However, multi-peak variations in N_e cannot be verified with the low resolution 2 Hz data as shown in the zoomed-in sections in Fig. 12. One of the drawbacks associated with the 16 Hz N_e data, as mentioned earlier, is that it is only recorded when the TII is inactive. Therefore, to check data availability, Table 1 summarizes the number of satellite passes per year for which 16 Hz N_e data were recorded. We used all the passes available as summarized in Table 1 and later realized that data accumulation for the period of study was enough for a climatology study.

Examples of Swarm's encounters with ionospheric irregularities are presented in Fig. 13. Figure 13 panel (a) shows multiple N_e depletions occurring between about $\pm 10^\circ - \pm 20^\circ$ QLat. From Fig. 13 panels (b) and (c), large values of both $\text{std}(dN_e)$ and $\text{std}(dN_e)/N_e$ often occur in locations of large depletions in N_e at the EIA crests close to the quasi-dipole equator,

Table 1. Summary of yearly total Swarm satellite passes over the low latitude region for which 16 Hz data was recorded.

Satellite	Total Swarm satellite passes per year					Total passes per satellite
Year	2014	2015	2016	2017	2018	
Swarm A	711	7,158	6,670	6,520	4,242	25,301
Swarm C	891	1,390	8,208	7,101	5,748	23,068
Swarm B	1,127	7,836	7,522	7,017	2,895	26,397

but also at the bottom of large scale bubbles. Based on the thresholds defined in Sect. 2 ($\text{std}(dN_e) > 0.25 \times 10^{10} \text{ m}^{-3}$ and $\text{std}(dN_e)/N_e > 0.01$) to identify plasma density structures, these depletions are ionospheric irregularities. The RTI is the most known mechanism that causes irregularities in low latitudes (Kelley, 2009; Kintner et al., 2007). The lower ionospheric layer declines 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. For such unstable arrangement, irregularities in the F - region at the bottom intensify and drift up, creating more complex plasma structures that extend to higher altitudes along magnetic field lines (Woodman and La Hoz, 1976; Abdu, 2005; Kelley, 2009). In general, ionospheric irregularities are more intense at the Equatorial Ionization Anomaly (EIA) belts ($\pm 15^\circ$ QLat) than at the geomagnetic equator as observed in Fig. 13. However, from Fig. 13, the event presented for Swarm A and C on 2015-03-07 shows high values of $\text{std}(dN_e)/N_e$ even at the magnetic equator. Huang et al. (2014) also observed that the relative and absolute perturbations were both able to capture fluctuations in ion density measurements made along C / NOFS tracks during 2008 – 2012 in the zonal direction. However, it was not possible to see a more detailed latitude distribution using C / NOFS satellite because it covered a small latitude range of about $\pm 13^\circ$ due to its low inclination angle of about 13° . The local time distribution characteristics of ionospheric irregularities were also determined and the results are presented and discussed in the following subsection.

3.1 Local Time Distribution of Ionospheric Irregularities

It is known from many studies (e.g. Kil and Heelis, 1998; Burke et al., 2004; Su et al., 2006; Stolle et al., 2006; Dao et al., 2011; Huang et al., 2014; Xiong et al., 2016b; Wan et al., 2018, etc) that ionospheric irregularities in the low latitudes occur after sunset. Here, we also check the local time dependence of the ionospheric irregularities identified on the N_e data from the Swarm faceplate to compare with previous results. Figure 14 presents the percentage occurrence of equatorial ionospheric irregularities as a function of local time based on (a) $\text{std}(dN_e)$ and (b) $\text{std}(dN_e)/N_e$. Using 16 Hz N_e data accumulated during the period of study, the seasonal dependence of local time distribution of ionospheric irregularities was also examined by grouping all the data into different seasons corresponding to March Equinox (Feb-Mar-Apr), June Solstice (May-Jun-Jul), September Equinox (Aug-Sep-Oct), and December Solstice (Nov-Dec-Jan). The number of irregularity structures was determined per one hour local time bin by counting the number of irregularity structures in a bin divided by the total number of observations.

As mentioned earlier, ionospheric irregularities in the low latitudes are nighttime phenomena and therefore, the analysis was restricted to the time period from 1800 LT-0600 LT. From Fig. 14, it is seen that irregularities occur from 1800 LT to 0600 LT

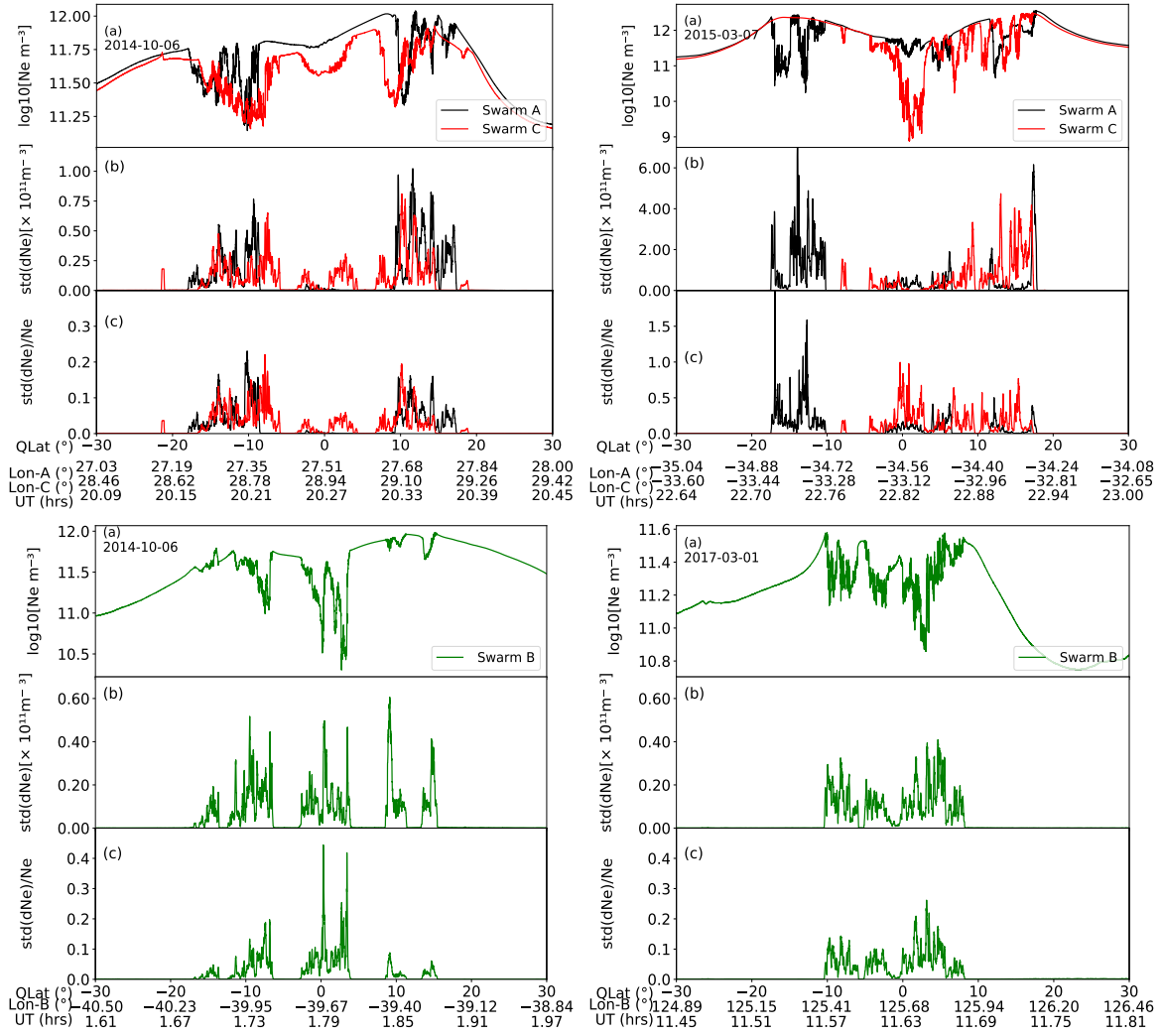
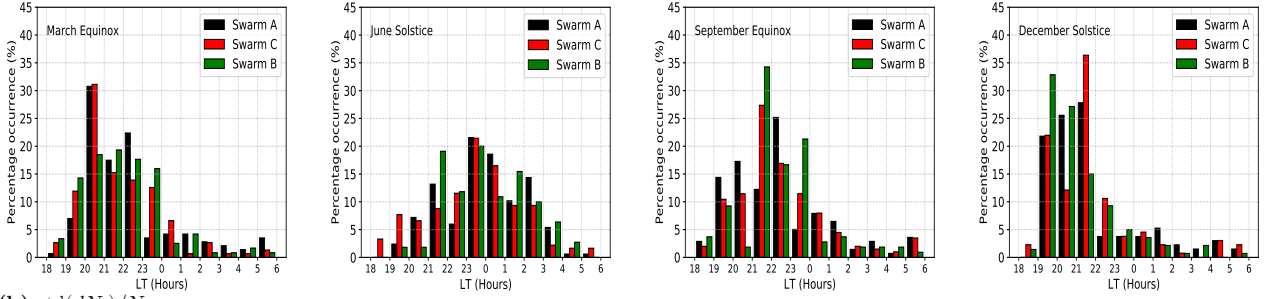


Figure 13. Irregularity structures observed by Swarm A, C, and B. Panels (a) to (c) represent electron density (N_e) variation at 16 Hz in logarithmic scale, absolute ($\text{std}(dN_e)$) and relative ($\text{std}(dN_e)/N_e$) electron density perturbations, respectively as functions of QLat, Geographic longitude (Lon), and Universal Time (UT).

as expected, irrespective of the method used. In Fig. 14, the highest percentage occurrence is observed in the equinoxes and December solstice, where the percentage increases faster between 1800 LT and 2000 LT, attaining a maximum at about 2100 LT and then decreases gradually till the morning hours. The increase in percentage occurrence from 1800 LT to 2100 LT can be attributed to increased eastward electric fields produced by the eastward thermospheric wind's electrodynamic interaction at the day-night terminator around the dip equator with the geomagnetic field (Rishbeth, 1971; Su et al., 2009). The increase in

(a) $\text{std}(dN_e)$



(b) $\text{std}(dN_e)/N_e$

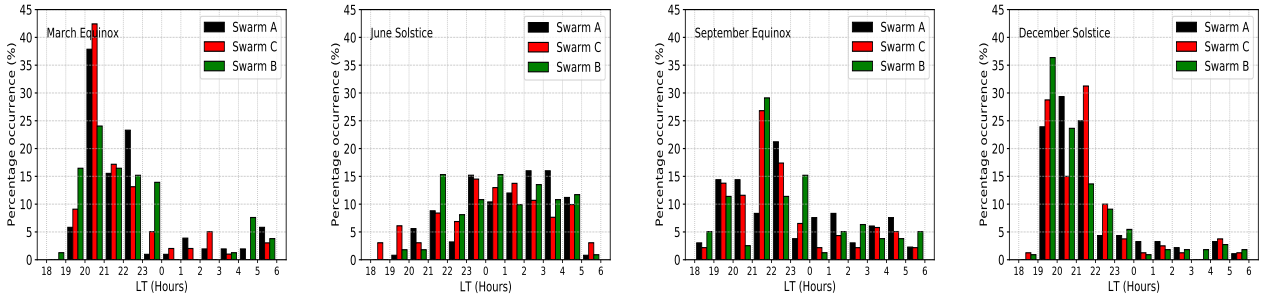


Figure 14. Histograms showing the percentage occurrence of (a) $\text{std}(dN_e) > 0.25 \times 10^{10} \text{ m}^{-3}$ and (b) $\text{std}(dN_e)/N_e > 0.01$ as a function of local time (LT) for the period from October 2014 - October 2018 for Swarm A, B, and C. Each panel presents a season.

the electric field to the east causes the night-side ionosphere to rise to higher altitudes where RTI is favored and this increases the occurrence of ionospheric irregularities (Fejer et al., 1999; Abdu, 2005; Su et al., 2009). The percentage occurrence of ionospheric irregularities is low in the June solstice and the percentage increase is slower with a wide plateau extending past midnight. According to Su et al. (2009), a late reversal of zonal drift associated with a small upward vertical post-sunset drift occurring at positive magnetic declination lengths in June solstice significantly inhibits irregularities. For the case of $\text{std}(dN_e)$, the percentage occurrence reduces towards morning hours, while $\text{std}(dN_e)/N_e$ maintains a high percentage occurrence past midnight in June Solstice. The percentage occurrence trend of $\text{std}(dN_e)$ -based irregularities is like that of Kil and Heelis (1998), Palmroth et al. (2000), Burke et al. (2004), Su et al. (2006), Stolle et al. (2006), Su et al. (2009), Xiong et al. (2016b), Wan et al. (2018), etc. The $\text{std}(dN_e)/N_e$ shows a nearly similar trend in percentage occurrence as for $\text{std}(dN_e)$ but with high occurrence post-midnight in June solstice. Increase in post-midnight irregularities quantified by relative perturbations has also been observed by Huang et al. (2011), Huang et al. (2012), Huang et al. (2014) and Dao et al. (2011) who used ion density measurements made by C / NOFS. The mechanisms that generate these post-midnight irregularities are still unknown and widely debated. **Two mechanisms to explain post-midnight irregularity have been suggested. One mechanism is the seeding of the RTI by atmospheric gravitational waves from below into the ionosphere, while the other mechanism is the elevation of the**

F-layer by the thermosphere's meridional neutral winds, which may be connected with the thermosphere's highest midnight temperature (Otsuka, 2018, and references therein).

The Global Positioning System - SCIntillation Network and Decision Aid (GPS - SCINDA) has often been used as one of the tools for measuring variations in radio signals' amplitude and phase. In the absence of GPS - SCINDA, many studies (e.g., Basu et al., 1999; Yang and Liu, 2015; Yizengaw and Groves, 2018) have shown that the rate of change of TEC index ($ROTI$) derived from Global Navigation Satellite System (GNSS) Total Electron Content (TEC) can be used as a proxy for quantifying scintillations. The $ROTI$ is defined as the standard deviation of Rate of Change of TEC (ROT) (Pi et al., 1997). Numerous studies have widely discussed these indices (e.g., Pi et al., 1997; Basu et al., 1999; Zou and Wang, 2009; Zakharenkova et al., 2016; Kumar, 2017; Yizengaw and Groves, 2018). We adopted $ROTI$ to compare the ground-based local time variations of irregularities/scintillations over different International GNSS Service (IGS) stations installed along the low latitude region with the variations presented in Fig. 14. The IGS stations considered are shown in Fig. 15 as red stars. The details of the IGS stations used are summarized in Table 2. To find $ROTI$, only signals from GPS satellites with elevation angle higher

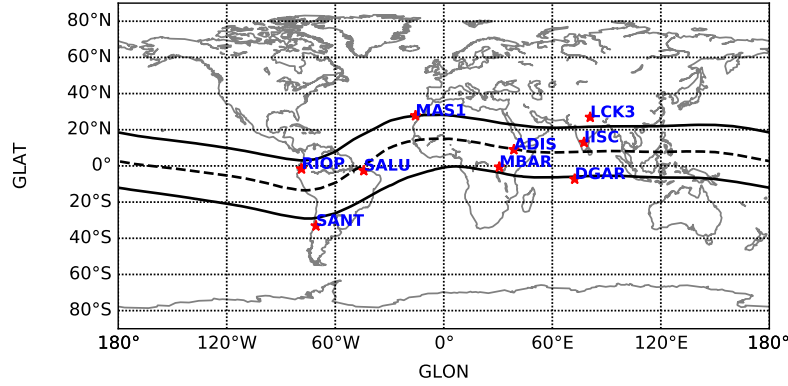


Figure 15. Map showing the location of IGS stations (red stars) considered in this study. The black dotted line represents the magnetic equator, while at about $\pm 15^\circ$ magnetic latitude the black solid lines represent the EIA belts.

than 25° over each independent station were considered to reduce the multipath effects. The $ROTI$ values > 0.5 TECU/min ($1 \text{ TECU} = 10^{16} \text{ el/m}^2$) were classified as irregularities/scintillations (Ma and Maruyama, 2006).

Figure 16 presents the percentage occurrence of $ROTI > 0.5$ TECU/Min in 1-hour local time bins for the different IGS stations and seasons. It is important to note that RIOP did not have TEC data in June solstice and September equinox as seen in panels (b) and (c) of Fig. 16. In general, the trend followed by local time distribution of $ROTI$ seems to closely agree with that of $\text{std}(dN_e)$ and $\text{std}(dN_e)/N_e$ in the equinoxes and December Solstice. As expected the percentage occurrence of ionospheric irregularities is higher mainly for the IGS stations in the African longitude even in June Solstice (Yizengaw et al., 2014). The percentage occurrence in June Solstice is generally small, comparable to that observed in Fig. 14, with a broad plateau extending post-midnight. However, the enhanced post-midnight irregularities seen in Fig. 14(b) for $\text{std}(dN_e)/N_e$ for June Solstice are not observed in the LT trend of $ROTI$. Therefore, the LT dependence of percentage occurrence of ionospheric

Table 2. Coordinates of IGS stations used in this study.

Station(Code)	Coordinates		
	Geog. lat (°)	Geog. lon (°)	Mag. lat (°)
Mbarara (MBAR)	-0.60	30.74	-10.2
Addis Ababa (ADIS)	9.04	38.77	0.18
Maspalomas (MAS1)	27.76	-15.63	15.63
Riobamba (RIOP)	-1.65	-78.65	10.56
Santiago (SANT)	-33.15	-70.67	-19.52
São Luis (SALU)	-2.59	-44.21	-0.25
Diego Garcia Island (DGAR)	-7.27	72.37	-16.89
Bangalore (IISC)	13.02	77.57	5.34
Lucknow (LCK3)	26.91	80.96	20.59

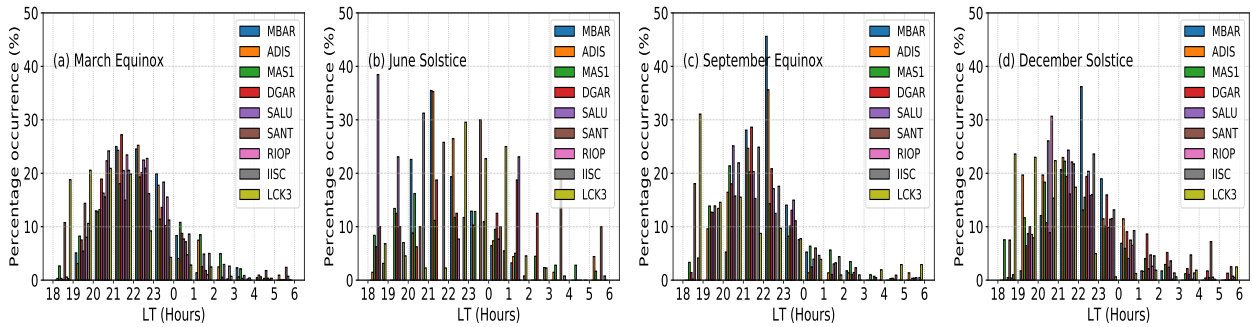


Figure 16. Percentage occurrence of $ROTI > 0.5$ TECU/Min in 1 hour LT bins for different stations (see legend).

irregularities quantified using $\text{std}(dN_e)$ closely follows the same trend as that of $ROTI$ for all seasons. The seasonal and longitudinal distribution of ionospheric irregularities is presented in the following subsection.

3.2 Seasonal and Longitudinal Distribution of Ionospheric Irregularities

The Swarm mission's 16 Hz N_e data collected over the 5-year period (2014 – 2018) has a credible global spatial and temporal coverage that is sufficiently good for examining the seasonal and longitudinal distribution of ionospheric irregularities in low latitudes. To check the seasonal and longitudinal variation of ionospheric irregularities, we concentrate on satellite passes within the local time range, 1800 – 0600 LT. The N_e data for the period of study was divided into four seasons as described in Sect. 3.1. Swarm equator crossings spanning the range of $-40^\circ - +40^\circ$ were considered since the study narrows down to the low latitude region. The $\text{std}(dN_e)$ and $\text{std}(dN_e)/N_e$ were calculated in bins of $3^\circ \times 4^\circ$ resolution in geographic latitude and

longitude. The occurrence rate of ionospheric irregularities does not always correspond to the highest amplitude of irregularity structures from the results presented by Wan et al. (2018). Therefore, here we concentrate on the magnitude of ionospheric irregularities other than the rate of occurrence. Zakharenkova et al. (2016) compared Swarm A and B 1-s N_e data and revealed satellite-to-satellite differences related to altitude, longitude, and local time. Here, we also show the results for all the three satellites separately. Figure 17 shows the seasonal and longitudinal distribution of $\text{std}(dN_e)$ during the period of study in

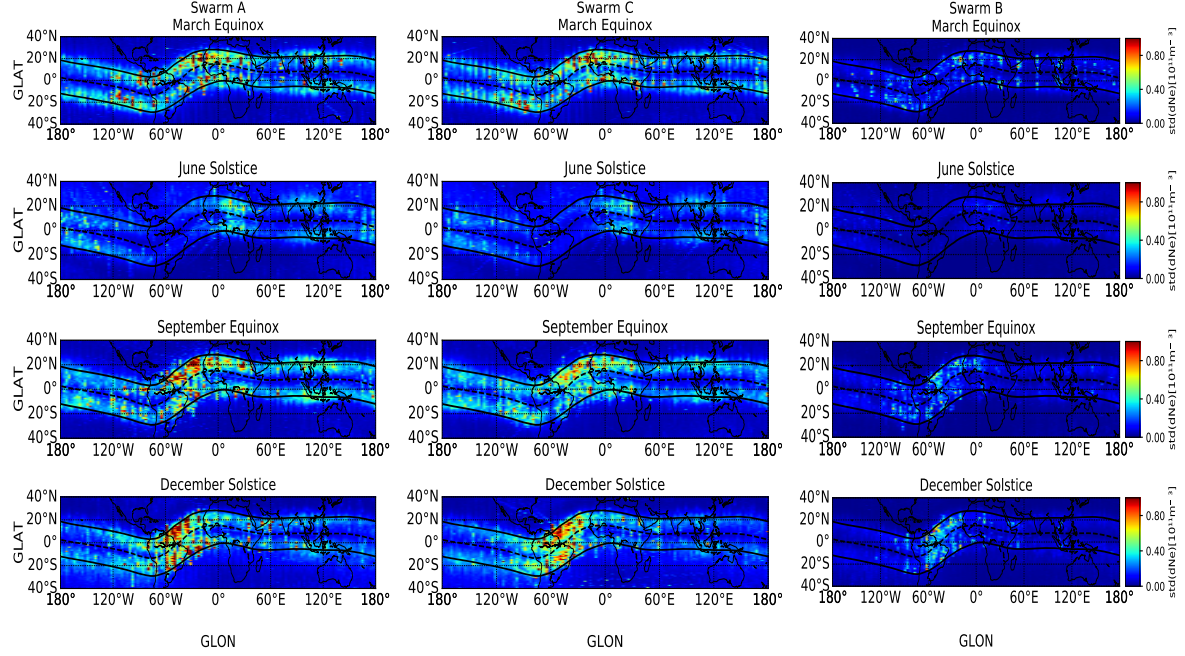


Figure 17. Absolute electron density perturbation ($\text{std}(dN_e)$) separated into four seasons (March/September equinox and June/December solstice) from October 2014 to October 2018 for Swarm A, C, and B. The black dotted line represents the magnetic equator, while the black solid lines represent the EIA Belts at about $\pm 15^\circ$ magnetic latitude. For each panel of a season, the color scales represent $\text{std}(dN_e)$.

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geographic coordinates, while Fig. 18 presents that of $\text{std}(dN_e)/N_e$ for Swarm A, C, and B independently in the first, second, and third columns, respectively. The different seasons are shown in the four panels from top to bottom.

The first noticeable feature in Fig. 17 and Fig. 18 is that almost all the irregularities occur within the EIA belts between about $\pm 15^\circ - \pm 20^\circ$ magnetic latitudes. However, Fig. 17 shows that absolute variations of $\text{std}(dN_e)$ are observed with a gap of low values at the magnetic equator, while in Fig. 18 maximum values of $\text{std}(dN_e)/N_e$ extend from the northern crest to the southern crest, including the magnetic equator. A clear picture of the density variations across the magnetic equator is seen in a scatter plot of the irregularities as a function of latitude as shown in Fig. 19. Some earlier studies (e.g., Burke et al., 2004; Su et al., 2006, etc) observed a normal-like distribution that peaks at the quasi - dipole equator and gradually decreases towards higher latitudes, reaching a minimum at around $\pm 30^\circ$ QLat, while others observed ionospheric irregularities concentrated around the northern and southern EIA belts (e.g., Liu et al., 2005; Stolle et al., 2006; Carter et al., 2013, etc). Only a few losses

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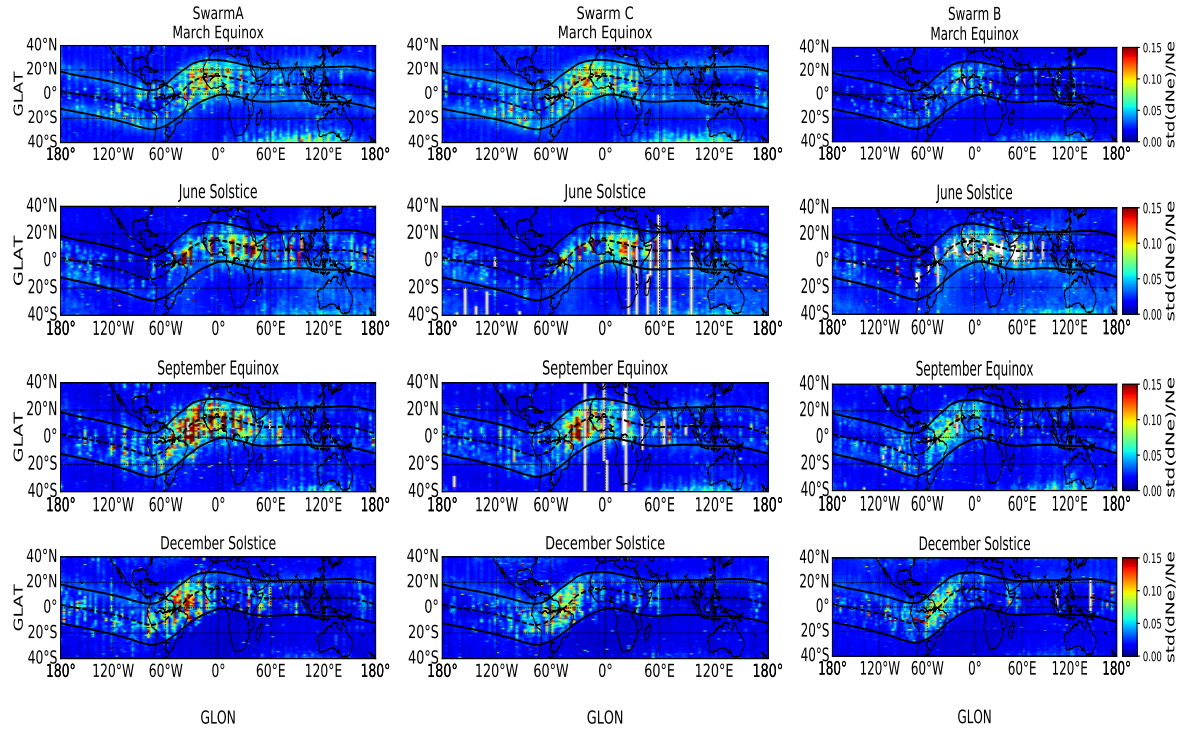


Figure 18. Relative electron density perturbation ($\text{std}(dN_e)/N_e$) separated into four seasons (March/September equinox and June/December solstice) from October 2014 to October 2018 for Swarm A, C, and B. The black dotted line represents the magnetic equator, while the black solid lines represent the EIA Belts at about $\pm 15^\circ$ magnetic latitude. For each panel of a season, the color scales represent $\text{std}(dN_e)/N_e$.

of the GPS tracks have been seen on the quasi-dipole equator (e.g, Buchert et al., 2015; Xiong et al., 2016a; Wan et al., 2018). Consequently, the variations in electron density at the quasi - dipole equator are relatively harmless to the GPS, the high-risk region being the high-density bands, north and south (Buchert et al., 2015).

Furthermore, there are differences between Swarm A / C and B in seasonal and longitudinal irregularity distribution. Swarm B shows the lowest values of both $\text{std}(dN_e)$ and $\text{std}(dN_e)/N_e$ compared to A and C. A similar observation was made by Zakharenkova et al. (2016) who compared the seasonal and longitudinal variation of ionospheric irregularities for only Swarm A and B during the years 2014 – 2015 using the 1-s N_e LP data. The differences observed between Swarm A/C and Swarm B can be explained by the altitude and local time separation between the satellites as Swarm B flies at a higher altitude and always crosses the post-sunset sector later than A and C.

In terms of seasons, high values of $\text{std}(dN_e)$ and $\text{std}(dN_e)/N_e$ are observed during the equinoxes at all longitudes especially in the African-Atlantic-South American regions. During June solstice, moderate values occur mostly in the African sector and the lowest values occur in the Atlantic-South American sector. During December solstice, high values are observed in the Atlantic-American sector. From the Indian Ocean to central Pacific sectors where the magnetic field declination is low, no

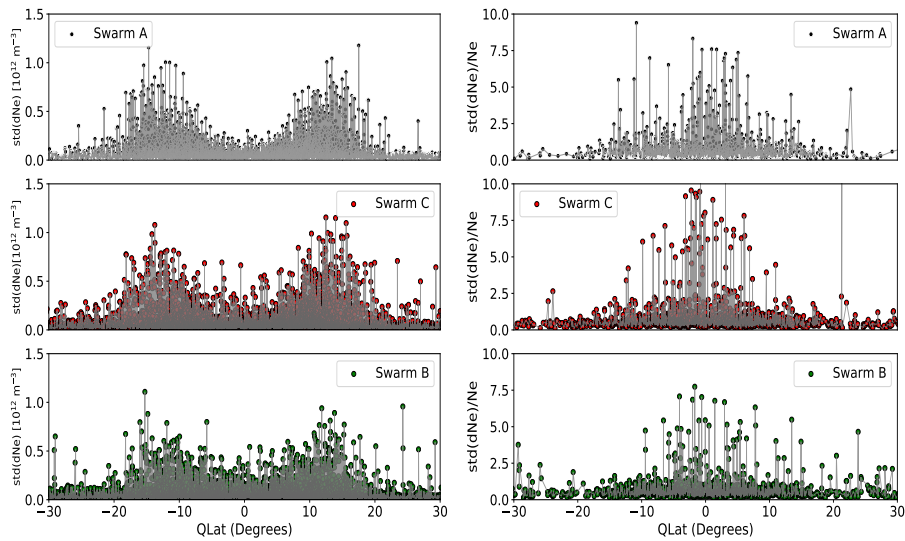


Figure 19. Scatter plots of latitude distribution of ionospheric irregularities observed for the period from October 2014 to October 2018. The left panel shows the distribution when irregularities are quantified using $\text{std}(dN_e)$, while the right panel shows the distribution when $\text{std}(dN_e)/N_e$ is used.

satellite detected many intense ionospheric irregularities in solstice seasons and in September equinox. Overall, the seasonal and longitudinal irregularity distribution shown in Fig. 6 and Fig. 7 is consistent with earlier studies irrespective of the criteria adopted (e.g., Su et al., 2006; Huang et al., 2001; Burke et al., 2004; Park et al., 2005; Huang et al., 2014; Zakharenkova et al., 2016; Wan et al., 2018). The RTI is known to intensify after sunset, causing severe irregularities when the day-night terminator is aligned with the plane of the magnetic field that occurs in the equinox (Tsunoda, 1985; Burke et al., 2004; Gentile et al., 2006; Yizengaw and Groves, 2018).

One of the challenges has been explaining the mechanism governing the longitudinal distribution of irregularities. Tsunoda (1985) proposed a model based on the magnetic declination to explain the distribution of ionospheric irregularities. However, this model could not explain the high occurrence of irregularities in June solstice over the African longitude. The longitudinal distribution of irregularities has also been attributed to gravity waves originating from the thermosphere (Yizengaw and Groves, 2018, and references therein). Yizengaw and Groves (2018) also added that the intertropical convergence zone (ITCZ) position, which are sources of gravity waves, may explain the longitudinal irregularity dependence observed. Kil et al. (2004) suggested that the longitudinal distribution at EIA latitudes of absolute electron density affects the occurrence of irregularities. Using DMSP data, Huang et al. (2001), Huang et al. (2002), and Burke et al. (2004) showed that the pattern of precipitation of the inner radiation belt's energetic particles explains the pattern of irregularities.

Among other parameters, the growth rate of equatorial ionospheric irregularities is controlled by the electron density gradient. Ionospheric irregularities in the equatorial and low latitudes can cascade upwards and along the magnetic field lines to the EIA belts characterized by high background N_e and steep gradients in density (Muella et al., 2010). From both local time and longitudinal perspectives, Wan et al. (2018) confirmed that the depletion amplitudes of irregularities are closely linked to the background electron density intensity. Xiong et al. (2016a) concluded that GPS signal reception may be interfered by small-scale plasma density structures with large-density gradients in zonal and meridional directions. Here, we attempt to compare the seasonal and longitudinal distribution of electron density gradient in the meridional direction along the tracks of the Swarm satellites with the magnitudes presented in Fig. 17 and Fig. 18. To determine the N_e gradient along the satellite tracks, N_e

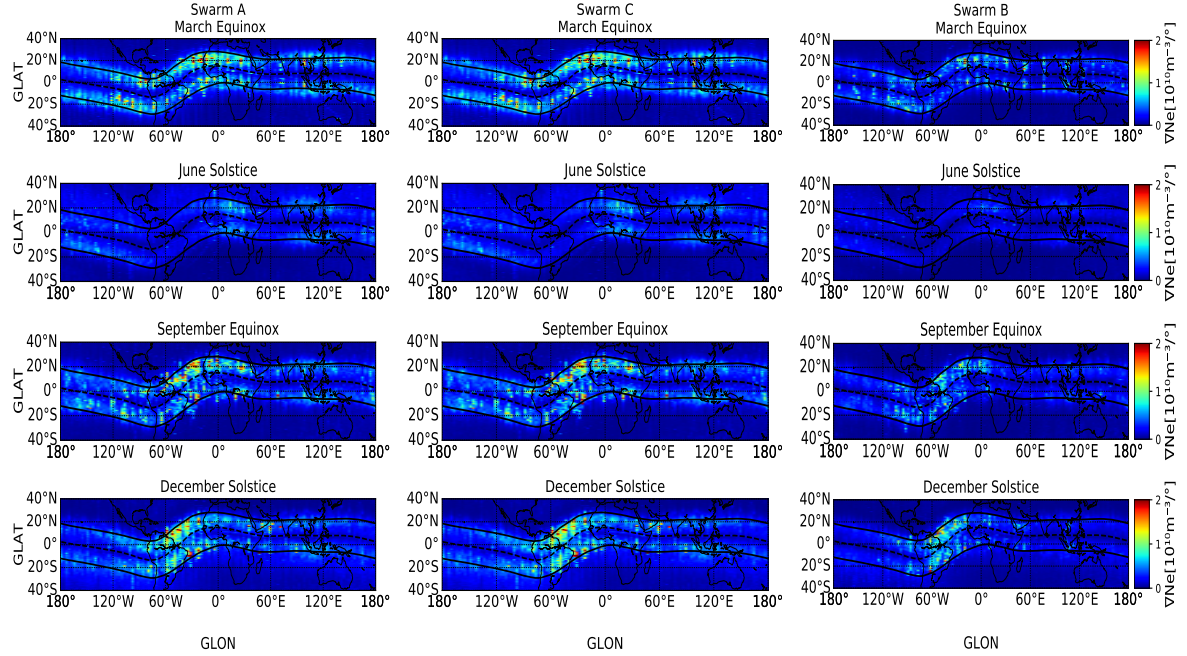


Figure 20. Along-track electron density gradient ∇N_e as derived from the Swarm satellites separated into four seasons (March/September equinox and June/December solstice) from October 2014 to October 2018 for Swarm A, C, and B. The black dotted line represents the magnetic equator, while the black solid lines represent the EIA belts at about $\pm 15^\circ$ magnetic latitude.

depletion was divided by the corresponding latitudinal distance in degrees. Figure 20 presents the N_e gradient, ∇N_e classified in different seasons for Swarm A, C, and B independently. The seasonal and longitudinal distribution of ∇N_e generally shows the same pattern as that of $\text{std}(dN_e)$ and $\text{std}(dN_e)/N_e$ with high values observed during the equinoxes and December solstice and moderate values in the African sector in June solstice. However, close inspection of Fig. 20 shows that the ∇N_e has the same latitudinal distribution as $\text{std}(dN_e)$ i.e., it is symmetrical about the magnetic equator with high values at the EIA belts. On the other hand, the latitudinal distribution of ∇N_e is different from that of $\text{std}(dN_e)/N_e$ (see Fig. 18). Earlier studies have also shown that irregularity events at latitudes of the EIA might be associated with the regions of strong density gradient (e.g, Basu

et al., 2001; Keskinen et al., 2003; Muella et al., 2008). The formation of small-scale irregularities appears to be more likely in ionospheric regions with higher background electron density and steep electron density gradients (Keskinen et al., 2003; Muella et al., 2008; Muella et al., 2010). Therefore, the amplitudes of ionospheric irregularities closely depend on background electron density (Wan et al., 2018) and steep N_e gradient globally as expected.

5 3.3 Magnetic and Solar Activity Dependence of Ionospheric Irregularities

The Swarm faceplate observations began near solar maximum in October 2014 and approached solar minimum of solar cycle 24 towards the end of 2018. Figure 21 shows the Kp index and 10.7 cm solar radio flux (F10.7) index in units of $10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1}$ to summarize the magnetic and solar activity for the period 2014 – 2018. In general, solar cycle 24 was

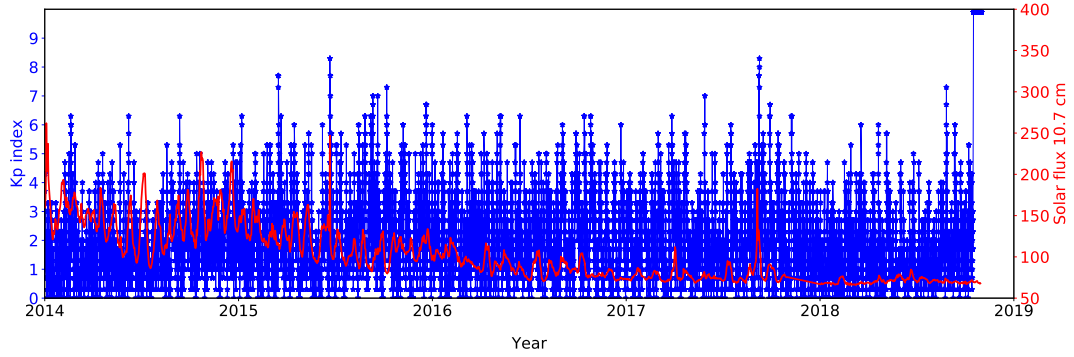
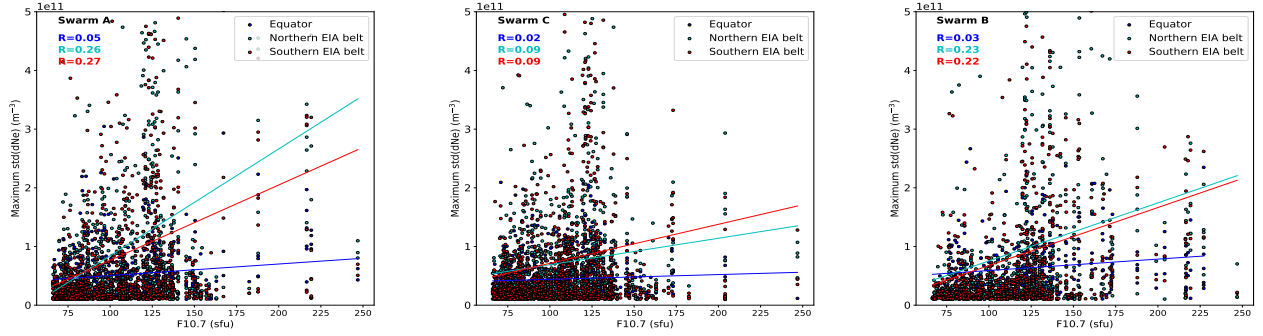


Figure 21. The 10.7 cm solar radio flux in solar flux units and the Kp index during 2014 – 2018.

characterized by very low solar activity compared to cycles that preceded it (Basu, 2013). The F10.7 varied often between about 50 sfu and 200 sfu for period 2014 – 2018. This period was also characterized by geomagnetic storms with $K_p > 3$. The effects of geomagnetic disturbances and changes in solar activity on ionospheric irregularity characteristics are of scientific interest and have been investigated in multiple studies (e.g. Palmroth et al., 2000; Sobral et al., 2002; Huang et al., 2002; Gentile et al., 2006; Stolle et al., 2006; Nishioka et al., 2008; Li et al., 2009; Basu et al., 2010; Sun et al., 2012; Carter et al., 2013; Huang et al., 2014). By using different criteria, Huang et al. (2014) determined the solar activity dependence of the occurrence of irregularities. In addition to solar activity, we also used different criteria to check the effects of magnetic variability on the distribution characteristics of irregularities in low latitudes.

Scatter plots of (a) $\text{std}(dN_e)$ and (b) $\text{std}(dN_e)/N_e$ as functions of F10.7 are shown in Fig. 22 for Swarm A, B, and C, independently. To check on the solar activity dependence of $\text{std}(dN_e)$ and $\text{std}(dN_e)/N_e$ at the equator and the EIA belts, the Swarm satellite passes were divided into three latitudinal ranges i.e, Equator ($\pm 5^\circ$ quasi-dipole latitude), Southern EIA region ($-30^\circ - -5^\circ$ quasi-dipole latitude), and Northern EIA region ($+5^\circ - +30^\circ$ quasi-dipole latitude) (see legend of Fig. 22). Each panel of Fig. 22 contains linear fits and the correlation coefficients R . In general, both $\text{std}(dN_e)$ and $\text{std}(dN_e)/N_e$ show weak positive correlation with F10.7 irrespective of the latitudinal range and this may be attributed to the small data-set used. However, it can be seen that the correlation between F10.7 and $\text{std}(dN_e)$ is higher at the EIA regions than at the equator.

(a) $\text{std}(dN_e)$



(a) $\text{std}(dN_e)/N_e$

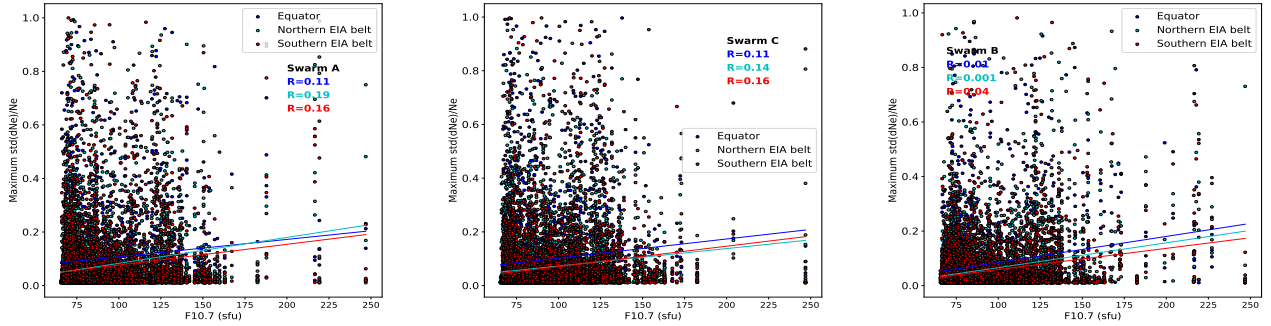


Figure 22. The distribution characteristics of (a) $\text{std}(dN_e)$ and (b) $\text{std}(dN_e)/N_e$ with respect to 10.7 cm solar radio flux in solar flux units for the period from October 2014 to October 2018. The black lines in each panel represent a linear fit to the data.

This also shows the symmetrical distribution of $\text{std}(dN_e)$ with high values obtained at the EIA belts than at the equator. There is hardly any difference observed between equatorial and off equatorial latitudes for the case of $\text{std}(dN_e)/N_e$. The results obtained for $\text{std}(dN_e)$ is consistent with that of Liu et al. (2007) who presented the solar activity dependence of the electron density at the equatorial anomaly regions.

- 5 For Swarm A alone, Fig. 12 shows the solar variation effect on seasonal and longitudinal distribution of $\text{std}(dN_e)$ and $\text{std}(dN_e)/N_e$. The results are divided into two major columns (distribution with respect to $\text{std}(dN_e)$ to the left and $\text{std}(dN_e)/N_e$ to the right). In each major column, there are two sub-columns, one for low solar activity ($F10.7 < 140$) and the other for moderate solar activity ($140 \leq F10.7 < 180$). It is important to point out that a reduced number of days were used to generate the climatology maps when $140 \leq F10.7 < 180$ compared to when $F10.7 < 140$. In Fig. 23, high $\text{std}(dN_e)$ values are often
- 10 observed when $140 \leq F10.7 < 180$. On the contrary, high values of $\text{std}(dN_e)/N_e$ are mostly observed when $F10.7 < 140$. The $F10.7$ dependence obtained using $\text{std}(dN_e)$ is similar to the results presented by Huang et al. (2001), Su et al. (2006),

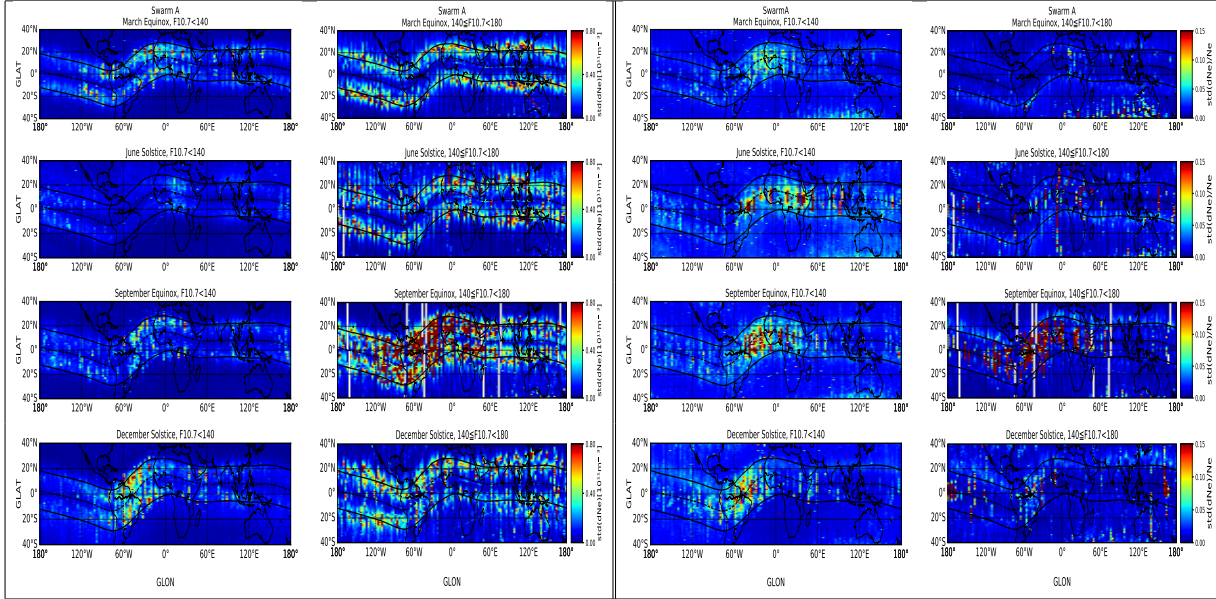
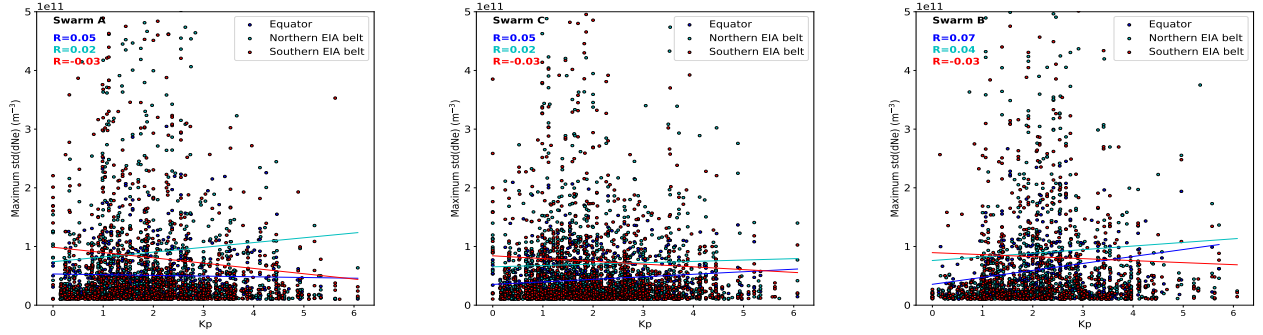


Figure 23. Solar activity effect on seasonal and longitudinal distribution of $\text{std}(dN_e)$ and $\text{std}(dN_e)/N_e$ for the period from October 2014 to October 2018: A case for Swarm A.

Stolle et al. (2006). It is necessary to note that Huang et al. (2001), Su et al. (2006), Stolle et al. (2006) addressed the solar activity dependence of the occurrence rate of ionospheric irregularities. Wan et al. (2018) presented differences between the occurrence rate of ionospheric irregularities and their amplitudes in terms of the latitudinal and longitudinal distribution. However, in general, the seasonal and longitudinal distribution of $\text{std}(dN_e)$ presented in Fig. 23 shows a similar dependence on different levels of F10.7 as the occurrence rates. Using simulations from the Magnetosphere - Thermosphere - Ionosphere - Electrodynamics General Circulation Model (MTIEGCM), Vichare and Richmond (2005) showed that upward evening drift increases at a similar rate in all longitude sectors with solar activity. Therefore, the high occurrence of irregularities during moderate or high solar activity period may be because of the atmospheric driver for the zonal electric field which intensifies during moderate/high solar activity, causing an increase in the RTI growth rate.

Figure 24 presents scatter plots of (a) $\text{std}(dN_e)$ and (b) $\text{std}(dN_e)/N_e$ as functions of Kp. To generate Fig. 24, the Swarm passes were also split into equatorial and EIA latitudes, similar to Fig. 22. In general, the results show a weak correlation with Kp close to zero, irrespective of the method used to quantify the level of equatorial ionospheric irregularities and the latitude range. Close inspection of Fig. 24 shows that the correlation between $\text{std}(dN_e)$ and Kp was lowest at the EIA belts compared to that at the equator. There is hardly any difference observed between equatorial and off equatorial latitudes for

(a) $\text{std}(dN_e)$



(a) $\text{std}(dN_e)/N_e$

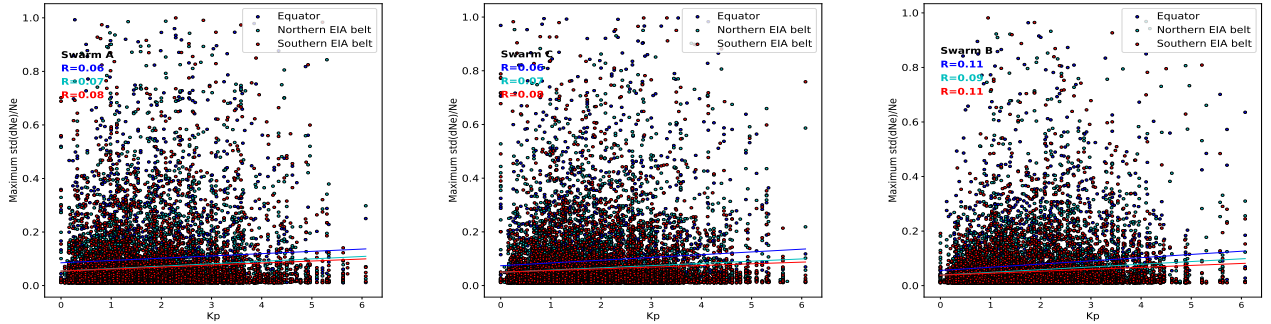


Figure 24. The distribution characteristics of (a) $\text{std}(dN_e)$ and (a) $\text{std}(dN_e)/N_e$ with respect to Kp index for the period from October 2014 to October 2018. The black lines in each panel represent a linear fit to the data.

the case of $\text{std}(dN_e)/N_e$. Dao et al. (2011) adopted the relative perturbation to quantify irregularities. Their reason for using the relative perturbation was that the absolute perturbation is correlated with the ambient ion density, which varies due to several factors such as varying altitude. The results shown in Fig. 22 and 24 also show that $\text{std}(dN_e)$ is more sensitive to solar and magnetic variations compared to $\text{std}(dN_e)/N_e$. The differences in the correlation between F10.7 or Kp and $\text{std}(dN_e)$ or $\text{std}(dN_e)/N_e$ at equatorial and off-equatorial latitudes can be explained by the differences in background electron density and electron density gradients at the crests and trough. Using DMSP pre-midnight plasma data, Huang et al. (2001) found that the rate of occurrence of irregularity and geomagnetic activity were negatively correlated. We also examined the geomagnetic effect on the seasonal and longitudinal distribution of irregularities as presented in Fig. 25 for Swarm A. The results are divided into two major columns (distribution with respect to $\text{std}(dN_e)$ to the left and $\text{std}(dN_e)/N_e$ to the right). In each major column, there are two sub-segments, one for calm geomagnetic occasions ($Kp < 3$) and the other for geomagnetically disturbed periods ($Kp \geq 3$). From Fig. 25, high values of both $\text{std}(dN_e)$ and $\text{std}(dN_e)/N_e$ are frequently observed when $Kp < 3$. Palmroth et al.

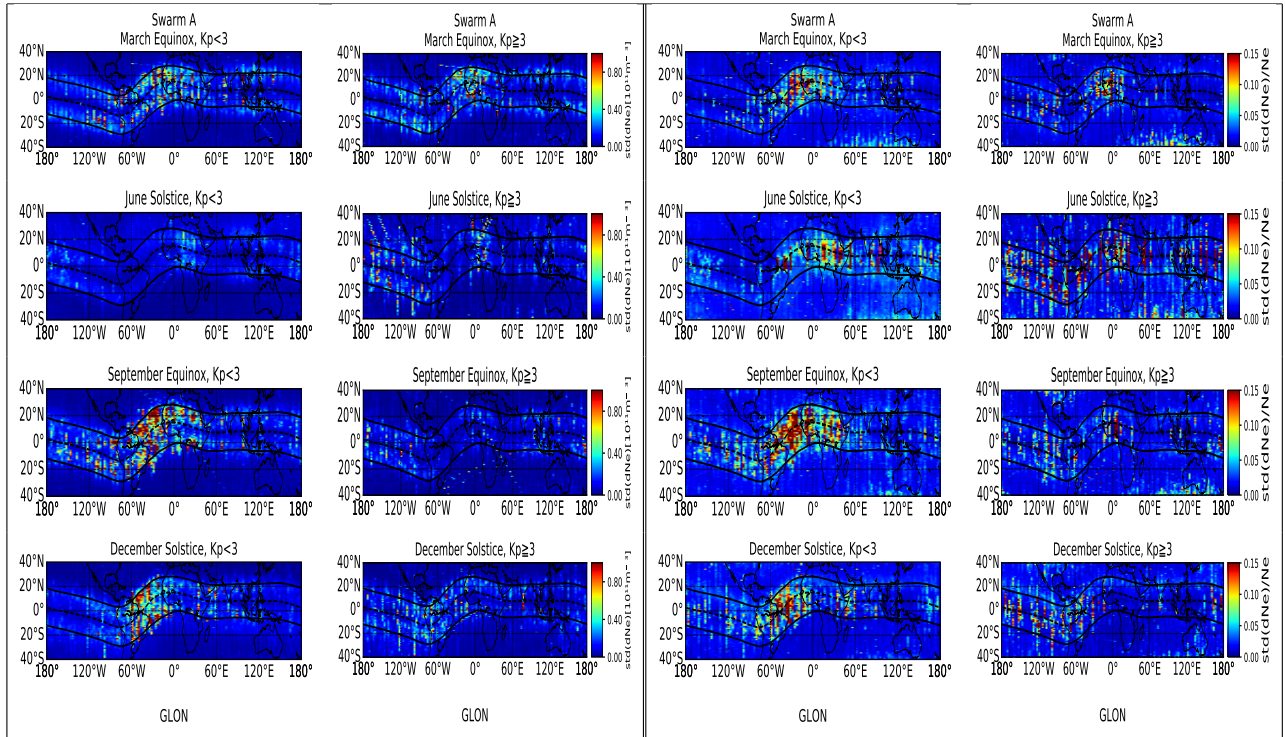


Figure 25. Geomagnetic effect on seasonal and longitudinal distribution of $\text{std}(dN_e)$ and $\text{std}(dN_e)/N_e$ for the period from October 2014 to October 2018: A case for Swarm A.

(2000) found a negative correlation between Kp and premidnight plasma depletions and a positive postmidnight correlation. They linked the distinction before and after local midnight to disturbed westward and eastward electrical fields, respectively. Stolle et al. (2006) checked the response of the occurrence of ionospheric irregularities to geomagnetic activity using magnetic field measurements made by CHAMP and they observed a weak relation between the occurrence of irregularities and the Kp index. Huang et al. (2001) also used DMSP measurements of plasma density and found that the occurrence rate of ionospheric irregularities for low Kp values were almost doubled compared to when Kp values are high. The geomagnetic activity affects irregularity occurrence in the low latitudes in two noteworthy ways i.e., by the brief entrance of auroral electric fields (Fejer, 1991; Kikuchi et al., 1996) and by the unsettling influence of dynamo effects (Blanc and Richmond, 1980). The second mechanism produces disturbance electric fields which last for a long time. The disturbance electric fields are westward after sunset (Blanc and Richmond, 1980; Huang et al., 2005; Abdu, 2012). It is important to note that the well-known trend in the longitudinal distribution of $\text{std}(dN_e)$ and $\text{std}(dN_e)/N_e$ for some seasons may not be clearly observed in Fig. 23 and Fig. 25 because of limited data after categorizing with respect to Kp or F10.7.

4 Conclusions

In this study, we have used Swarm N_e data measured by the faceplate at a frequency of 16 Hz to examine the distribution characteristics of ionospheric irregularities in the equatorial and low latitude ionosphere from 2014–2018 when the 16 Hz data was available. Two methods (absolute and relative perturbation) were used to quantify the level of ionospheric irregularities.

- 5 Both methods were able to capture fluctuations in electron density along single satellite passes. Basing on the large number of Swarm low latitude crossings for the years 2014 – 2018, the local time, seasonal and longitudinal distribution of ionospheric irregularities in the low latitudes were examined. We demonstrated the importance of steep density gradients for the generation and distribution of ionospheric irregularities in the low latitudes. We also checked the effects of geomagnetic and solar activity on the distribution characteristics of ionospheric irregularities. The findings are summarized below:
- 10 (i) The local time distribution of irregularities quantified by the two methods showed that they are mainly nighttime phenomena as expected. Both $\text{std}(dN_e)$ and $\text{std}(dN_e)/N_e$ showed similar trends in percentage occurrence during the equinoxes and December solstice with a peak occurrence between 2000 LT and 2200 LT. The percentage occurrence was lowest in June solstice. Generally, the local time dependence of ionospheric irregularities is not much different when either $\text{std}(dN_e)$ or $\text{std}(dN_e)/N_e$ is used. However, the local time distribution according to $\text{std}(dN_e)$ is closely related to that of $ROTI$ derived from ground-based stations.
- 15 (ii) In general, the seasonal and longitudinal distribution of ionospheric irregularities as quantified by the Swarm 16 Hz N_e data was in agreement with past observations using other satellite missions irrespective of the method used. However, close inspection of the magnetic latitudes reveals that $\text{std}(dN_e)$ and $\text{std}(dN_e)/N_e$ showed different latitudinal distribution of ionospheric irregularities about the magnetic equator. The $\text{std}(dN_e)$ showed a symmetric distribution about the magnetic equator with high magnitudes at latitudes of about $\pm 10^\circ - \pm 15^\circ$. **The $\text{std}(dN_e)/N_e$ showed a peak at the quasi-dipole equator which gradually decreased towards higher latitudes.**
- 20 (iii) The seasonal and longitudinal distribution of electron density gradient was closely related to that of $\text{std}(dN_e)$ and $\text{std}(dN_e)/N_e$. Also, symmetry about the magnetic equator was observed with ∇N_e . Therefore, in addition to the background electron density presented by Wan et al. (2018), the longitudinal distribution of ionospheric irregularities also depends on steep electron density gradients as expected.
- 25 (iv) **The $\text{std}(dN_e)$ showed a weak positive correlation with $F10.7$ and the correlation was even lower with $\text{std}(dN_e)/N_e$. Furthermore, $\text{std}(dN_e)$ in the EIA crest regions grew approximately linearly from the low to moderate solar activity, with higher correlation than that in the EIA trough region. The $F10.7$ dependence of the seasonal and longitudinal distribution of the ionospheric irregularities showed slightly different trends between $\text{std}(dN_e)$ and $\text{std}(dN_e)/N_e$. The discrepancy between the two methods may be because of the limited data. In general, the distribution of ionospheric irregularities was still lower during the geomagnetically disturbed period than in quiet times. The correlation between $\text{std}(dN_e)$ and Kp was lowest at the EIA belts compared to that at the equator. The solar and magnetic activity dependence of $\text{std}(dN_e)/N_e$ hardly showed any difference in correlation between equatorial and off-equatorial latitudes.**
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Despite the obvious limitations of using polar-orbiting satellites to monitor equatorial electrodynamics, Swarm has provided credible distribution characteristics of ionospheric irregularities in the low latitude region with data accumulated in five years (2014 – 2018). In general, the initial observations of the distribution characteristics of ionospheric irregularities using the 16 Hz N_e data are in good agreement with earlier works that have addressed similar concepts. This has demonstrated the ability of Swarm faceplate N_e data for ionospheric studies. Therefore, the 16 Hz faceplate data is a useful measurement that can be adopted in order to understand ionospheric irregularities.

Data availability. The official website of Swarm is <http://earth.esa.int/swarm> and <ftp://swarm-diss.eo.esa.int> is the server for the distribution of Swarm data. IGS/GPS data for the equatorial and low latitude stations were downloaded from <http://garner.ucsd.edu/pub/rinex/>. The Kp index and F10.7 solar radio flux data used in this study were obtained from the website <http://omniweb.gsfc.nasa.gov/>.

Author contributions. Aol Sharon, Stephan Buchert, and Edward Jurua designed the concepts and implemented them. Aol Sharon prepared the manuscript with contributions from all co-authors.

Competing interests. No competing interests are present.

Acknowledgements. This study was sponsored by the International Science Program (ISP) of the Uppsala University, Sweden. The authors acknowledge ESA Swarm team for the Swarm mission and for providing the Swarm data. The official Swarm website is <http://earth.esa.int/swarm>, and the server for Swarm data distribution is <ftp://swarm-diss.eo.esa.int>. IGS/GPS data for the equatorial and low latitude stations were downloaded from <http://garner.ucsd.edu/pub/rinex/>. The Kp index and F10.7 solar radio flux data used in this study were obtained from the website <http://omniweb.gsfc.nasa.gov/>.

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