Response to Reviewer 2 comments

The authors of this manuscript thank the reviewer for the suggestions. Our response to the comments and suggestions are presented below.

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 lat- itudes, 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 will be improved in this respect. As a new aspect which is possibly relevant for especially the small-scale irregularities we have analyzed the along-track gradient of Ne (as a proxy of the pressure gradient).

Major Comments

(1) 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: We thank the reviewer for the suggestion and this will be emphasized in the revised manuscript.

(2) 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 appreciate the reviewer for the valuable comment. 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 12-13 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.

(3) P13 Line10 – 12: Obviously, the s/l variation of ∇N_e is similar to ΔN_e but not $\Delta N_e/N_e$, authors should describe the plots objectively.

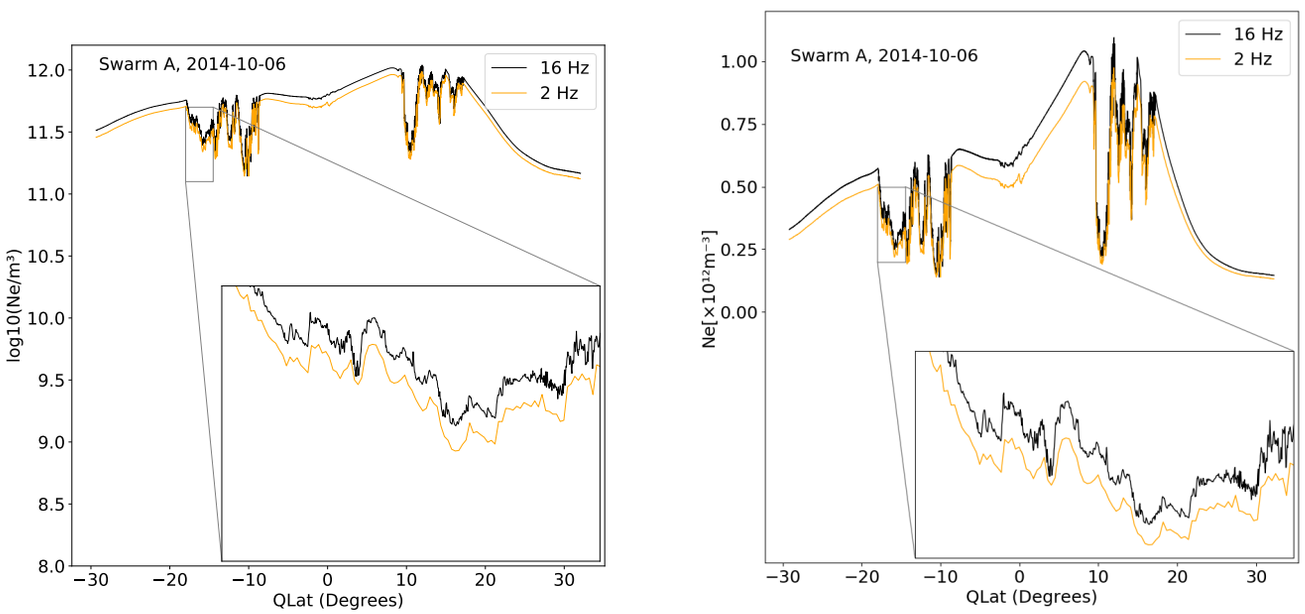
Response: The seasonal and longitudinal distribution of ∇N_e generally shows the same pattern as that of ΔN_e and $\Delta N_e/N_e$ with high values observed during the equinoxes and December solstice and moderate values in the African sector in June solstice. However, close inspection of Figure 9 shows that the ∇N_e has the same latitudinal distribution as ΔN_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 $\Delta N_e/N_e$. 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,https://doi.org/10.1029/2001ja001116; Keskinen et al., 2003,https://doi.org/10.1029/2003gl017418). 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,https://doi.org/10.1029/2003gl017418; Muella et al. 2008,https://doi.org/10.1029/2007ja012605; Muella et al. 2010,https://doi.org/10.1029/2009JA014788). Therefore, the amplitudes of ionospheric irregularities closely depend on background electron density (Wan et al. 2018) and steep N_e gradient globally, as expected. We shall describe the plots objectively in the revised manuscript.

Minor comments:

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

Response: We thank the author for the recommendation. However, the trend is similar whether the absolute or logarithmic scale is adopted for Figure 1. We present here a comparison for Swarm A on 2014-10-06.



(2) 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. The sentence will be rephrased to make it more clear.

(3) 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 were suggested to explain the occurrence of post-midnight irregularity. One mechanism is the seeding of the RTI by atmospheric gravity waves originating from below into the ionosphere, while the other mechanism is the elevation of the F-layer by the meridional neutral winds in the thermosphere, which may be associated with the maximum midnight temperature in the thermosphere (Otsuka, 2018, https://doi.org/10.1186/s40645-018-0212-7, and references therein). The sentence will be rephrased to make it clear.

(4) 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: We thank the reviewer for the observation. The IGS station RIOP did not have data in June solstice and September equinox. This information will be included in the revised manuscript.

(5) 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. In fact, 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

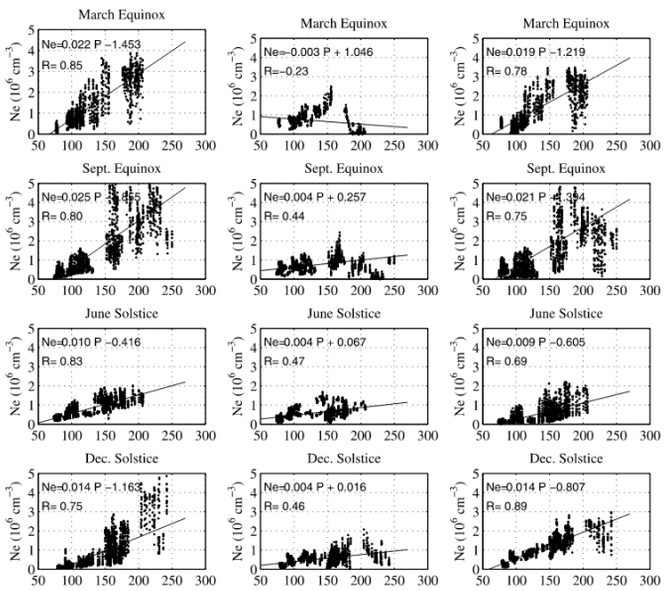


Figure 8. Same as Figure 7 but for postsunset (1800−2300 MLT) sector for the (left) northern EIA crest, (middle) dip equator, and (right) southern EIA crest.

results presented by Liu et. al. 2007, the electron density in the crest regions of the EIA grows roughly 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 and the result is presented in Figure 1 for Swarm A. We divided the Swarm satellite passes into three latitudinal ranges i.e, Equator (±5° quasi-dipole latitude), Southern EIA region (-30°− -5° quasi-dipole latitude), and Northern EIA region (+5°−+30° quasi-dipole latitude). A summary of the latitudinal ranges is presented in a map in Figure 2. 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 std(dN_e) is higher at the EIA regions than at the equator. Similar observation was made for Swarm C and B (not presented here). This shows also the symmetrical distbution of std(dN_e) with high values obtained at the EIA belts than at the equator as seen in Fig. 6. For the case of std(dN_e) dependence on Kp, it is a generally weak correlation and it is more negative at the equator than off equatorial latitudes. For std(dNe)/dNe, 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 std(dNe) is consistent with that of Liu et. al. 2007, but std(dNe)/Ne shows discrepancies with the results of Liu et al 2007. Our study was designed to focus specifically on the geomagnetic and solar activity dependence of the seasonal and longitudinal distribution of ionospheric irregularities particularly for Figures 11 and 13 this time. However, we will consider including the results presented in Figure 1. Thank you for the suggestion.

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

Response: 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 Ne gradient globally, as expected. This will be corrected in the revised manuscript.

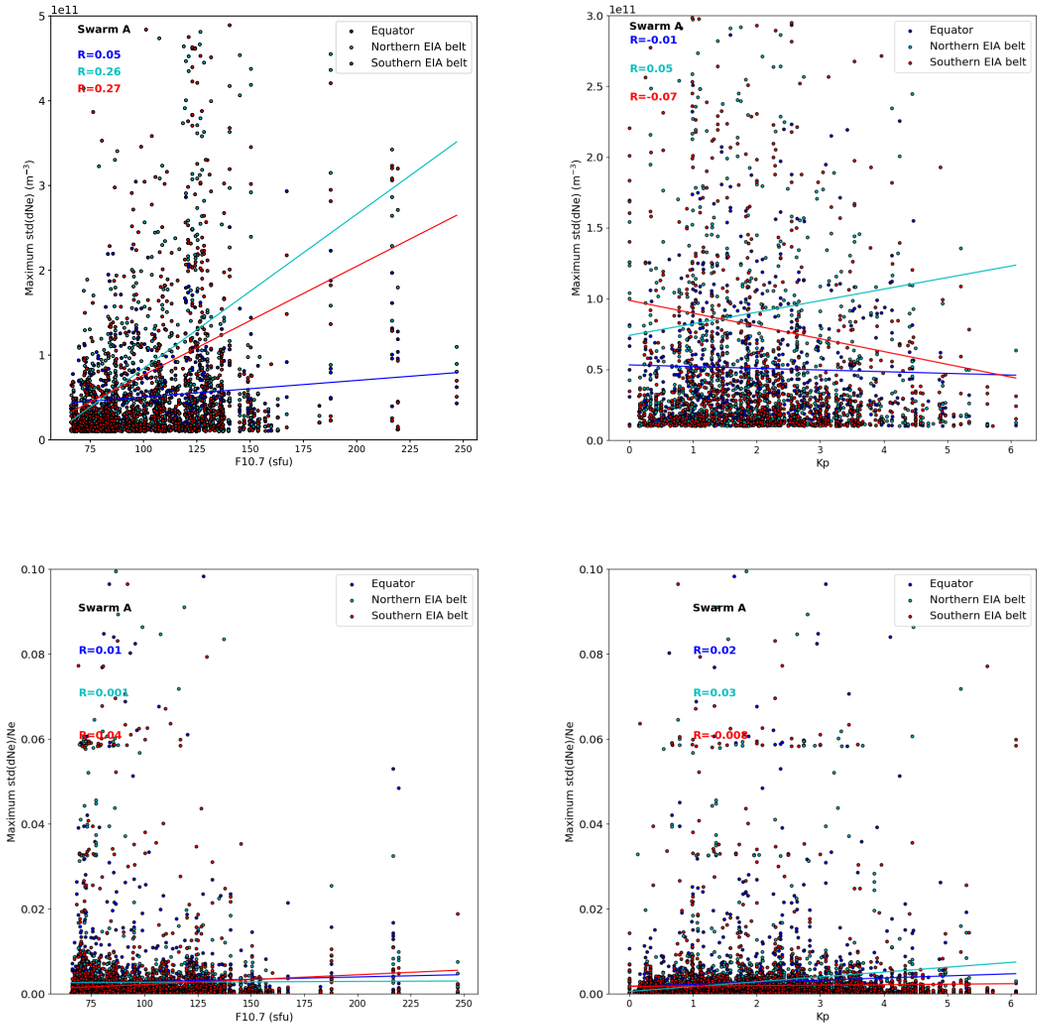


Figure 1: The distribution characteristics of (a) std(dN e) and (b) std(dN e)/N e with respect to 10.7 cm solar radio flux in solar flux units and kp for the period from October 2014 to October 2018.

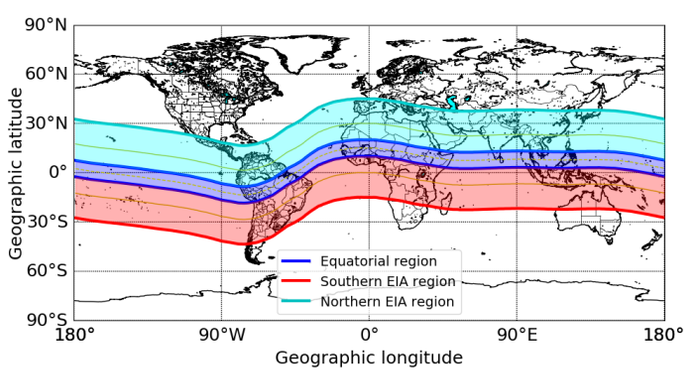


Figure 2: A summary of the latitudinal ranges

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

Response: This will be rephrased to, "The $\Delta N_e/N_e$ shows a peak at the quasi-dipole equator which gradually

decreases towards higher latitudes" in the revised manuscript.

(8) 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.14 will be rephrased to ,"Geomagnetic effect on seasonal and longitudinal distribution of ΔN_e and $\Delta N_e/N_e$ for the period from October 2014 to October 2018: A case for Swarm A." and this will also be corrected in the revised manuscript.

Final Remark: We thank the reviewer for the multiple comments.