remote sensing

Communication

Investigation of the Topside Ionosphere over Cyprus and Russia Using Swarm Data

Haris Haralambous [1,2,*], Krishnendu Sekhar Paul [1], Arun Kumar Singh [3] and Tamara Gulyaeva [4]

1 Frederick Research Center, Nicosia 1303, Cyprus
2 Department of Electrical Engineering, Computer Engineering and Informatics, School of Engineering, Frederick University, Nicosia 1036, Cyprus
3 CSIR-Central Glass and Ceramic Research Institute, Kolkata 700032, India
4 The Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radiowave Propagation of the Russian Academy of Sciences (IZMIRAN), Moscow 108840, Russia
* Correspondence: eng.hh@frederick.ac.cy

Abstract: Using the topside electron density (Ne) measurements recorded over Cyprus and Russia, we investigate the latitudinal variation in the topside electron density during the interval 2014–2020, encompassing a period of high-to-low solar activity. The selected topside electron density dataset employed in this study is based on the in situ Langmuir probe data on board the European Space Agency (ESA) Swarm satellites, in the vicinity of the three Digisonde stations in Nicosia (35.14°N, 33.2°E), Moscow (55.5°N, 37.3°E) and Saint Petersburg (60.0°N, 30.7°E). Our investigation demonstrates that the ratio $Ne_{\_Swarm}$/NmF2 between the coincident $Ne_{\_Swarm}$ and the Digisonde NmF2 observations is higher than one on various occasions over Nicosia during the nighttime, which is not the case over Moscow and Saint Petersburg, signifying a discrepancy feature of the electron density at Swarm altitudes which depends not only on the solar activity and time of day but also on the latitude.

Keywords: topside ionosphere; electron density; Swarm satellite mission; Langmuir probe; Digisonde

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Citation: Haralambous, H.; Paul, K.S.; Singh, A.K.; Gulyaeva, T. Investigation of the Topside Ionosphere over Cyprus and Russia Using Swarm Data. *Remote Sens.* **2023**, *15*, 1344. https://doi.org/10.3390/rs15051344

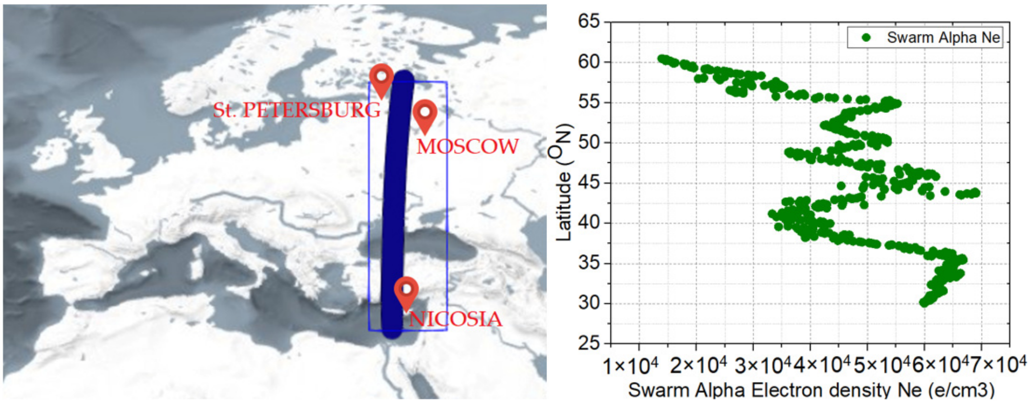
Academic Editor: Saioa A. Campuzano

Received: 1 February 2023
Revised: 23 February 2023
Accepted: 25 February 2023
Published: 27 February 2023

1. Introduction

The topside ionosphere over the peak electron density in the F2 region encapsulates a significant percentage of the total electron content (TEC). Therefore, the study of its morphology through various measurement techniques is crucial. Despite the fact that ionosondes have been the primary instrument for 24/7 remote sensing of the bottomside ionosphere, their limitation to probe up to the peak height of the F2 layer at a specific location led to the development of alternative techniques for monitoring the topside ionosphere on a global scale. Such techniques were applied in satellite-based missions in the past and present, including topside sounders [1] and radio occultation missions [2] for remote sensing the full topside electron density profile. On the other hand, Langmuir probes (LP) on board low Earth orbit (LEO) satellites facilitate in situ electron density monitoring at a fixed altitude and have also been incorporated on several present and past satellite mission payloads [3–6]. Swarm is one of these missions that has been in operation since 2013. Deployed by the European Space Agency (ESA), it is based on three identical satellites in a circular near-polar orbit at an 87.75° inclination with a primary scientific focus on the study of the magnetic field of the Earth. During the early stages of the mission, all three satellites were flying at an altitude of 500 km, but subsequently, Swarm A and C were placed at a 460 km orbit while maintaining a longitudinal separation of about 1.4° and Swarm B to an approximate altitude of 530 km. A primary instrument on all three satellites is an electric field instrument (EFI) [7], which records measurements of the plasma density, velocity and drift at a high resolution. The EFI carries a pair of Langmuir probes (LP) that measure the in-situ electron density, electron temperature and electric potential from the high gain probe at 2 Hz. Comparison studies incorporated the Swarm data and collocated Digisonde soundings for local bottomside and topside ionospheric studies [8].

In the frames of a bilateral project between Cyprus and Russia, an investigation was undertaken concerning the latitudinal electron density variation over a narrow strip encapsulating an area which is covered by three Digisondes (Figure 1). A preliminary study performed over Nicosia and Moscow [9] over the low solar activity year of 2020 demonstrated that Swarm satellites occasionally exhibit dramatically higher topside Ne values than the peak electron density of the electron density profile (NmF2). This was identified only during the nighttime which indicates that it is caused under specific conditions and not due to random expected uncertainties inherent to the Langmuir probe measurement technique. This is not expected as it contradicts the existing topside ionospheric model formulations such as the IRI which predicts that the ionosphere exhibits an electron density peak (NmF2) at hmF2 and then decreases as a function of height beyond hmF2 in accordance with the Chapman layer theory [10,11]. Particularly for the low solar activity year of 2020, the ratio Ne_{Swarm}/Digisonde NmF2 exceeded 1 during the nighttime (0–4 LT and 20–24 LT), reaching values up to 1.5 for the Nicosia station. That is a notable finding because $Ne\_{Swarm}/NmF2 > 1$ indicates that the topside electron density can exceed the peak electron density of the F2 layer over Nicosia during the nighttime, which is rather unexpected. The main finding of that preliminary investigation attributed these extraordinary values of the Ne_{Swarm} during the nighttime to the long-lasting latitudinal four-peak structure in the nighttime ionosphere observed by the Swarm constellation. Xiong et al. [12] studied the four-peak structures in the nighttime ionosphere and they reported that two mid-latitude peaks appear close to the $\pm 40°$ magnetic latitude, while the two low-latitude peaks appear within the $\pm 20°$ magnetic latitude. Such latitudinal four-peak structures can persist throughout the night until the sunrise hours. No clear seasonal dependence is found for the two mid-latitude peaks, while the two low-latitude peaks are almost symmetric about the magnetic equator during equinoxes but are located at slightly higher latitudes in the summer hemisphere around solstices. A recent paper by Cai et al. [13] revealed that on certain days, an extra electron density peak is formed after sunset which was attributed to the depletion of the plasma density between approximately 15° and 25°S. Although quiet-time TEC increases have been reported over Nicosia during low solar activity years, we cannot justify the excessive Ne_{Swarm}/NmF2 increases because we have to consider that relative changes would be reflected both on topside electron densities and NmF2 [14]. Furthermore, Xiong et al. [12] have reported that such cases are found only in 4% of the Swarm passes which contradicts our results that indicate a much more systematic effect. This is further explored in this paper by extending this investigation to a more extended temporal and geographical scope, encapsulating measurements from high-to-low solar activity (2014 to 2020) and also over the higher latitude station of Saint Petersburg. Therefore, in the present study, we exploited the Swarm A and B and C topside electron density measurements within 2° of Nicosia (35.14°N, 33.2°E), Moscow (55.5°N, 37.3°E) and Saint Petersburg (60.0°N, 30.7°E) along with the simultaneous Digisonde F2-layer peak electron density NmF2 recordings at the three stations to investigate the temporal features of the ratio Ne_{Swarm}/NmF2 over this narrow longitude range, as shown in Figure 1. To verify our findings, we have also used the COSMIC-1 electron density at the Swarm B altitude and the corresponding COSMIC-1 NmF2 values over the three stations under consideration.



(**a**) (**b**)

Figure 1. (**a**) Swarm A projection and (**b**) corresponding Ne variation vs. latitude.

2. Data

With respect to the quality of Swarm electron density ($Ne_{\_Swarm}$), the quality flag ($\leq$29) and the Ionospheric Plasma Irregularities (IPIR) index (<3) were considered in accordance to the guidelines of Swarm L2 product data. Maximum electron density at the F-layer peak values (NmF2) were selected on the basis of time coincidence at a maximum of 7.5 min from any Swarm A, B or C passage over the Digisonde stations.

Figure 1 shows an example of Swarm A passage in the vicinity of the three stations and the corresponding latitudinal electron density profile at an altitude of 460 km. By selecting an appropriate longitude range within 33–61° in latitude and 32–38° in longitude, we have gathered a considerable number of such passes in the vicinity of the three stations (within 0.5° in latitude and 2° in longitude) for the interval 2014–2020 which covered high-to-moderate (2014–2016) and moderate-to-low (2017–2020) solar activity levels in solar cycle 24. These numbers were sufficient to draw some interesting conclusions regarding topside electron density at Swarm altitudes by exploiting the accuracy at which NmF2 is measured by Digisondes.

3. Analysis

Figures 2 and 3 show the local time variation in the ratio of $Ne_{\_Swarm}$/Digisonde NmF2 ($Ne_{\_Swarm}$/NmF2) for all the passes considered over Moscow and Nicosia for Swarm A and B, respectively. For this long-term comparison, in the interval 2014–2020, we have used only the Moscow and Nicosia data because the Saint Petersburg Digisonde became operational after 2017. We must note that for these $Ne_{\_Swarm}$/NmF2 ratios, NmF2 was determined from manually scaled ionograms to ensure accurate Digisonde ionospheric representation at the F2-layer electron density peak. As it can be seen from these graphs, for all years and both solar cycle phases (high to moderate in Figure 2 and moderate to low in Figure 3), the $Ne_{\_Swarm}$/NmF2 is less than 1 (as expected) during the daytime and increases during the nighttime (0–4 LT and 20–24 LT) as hmF2 increases, for both stations. However, for the moderate-to-low solar activity years (2017–2020), the $Ne_{\_Swarm}$/NmF2 during the nighttime $Ne_{\_Swarm}$/NmF2 over Nicosia exhibits values up to 1.5, as indicated in Figure 3. This is a notable finding because $Ne_{\_Swarm}$/NmF2 > 1 indicates that the topside electron density can exceed the peak electron density of the F2 layer over Nicosia during the nighttime, which is not reasonable and unexpected. This effect seems to become more pronounced as the solar activity decreases from 2014 to 2020 which is also depicted on the percentage of the values Ne/NmF2 $\geq$ 1 for each year, as shown in Table 1.

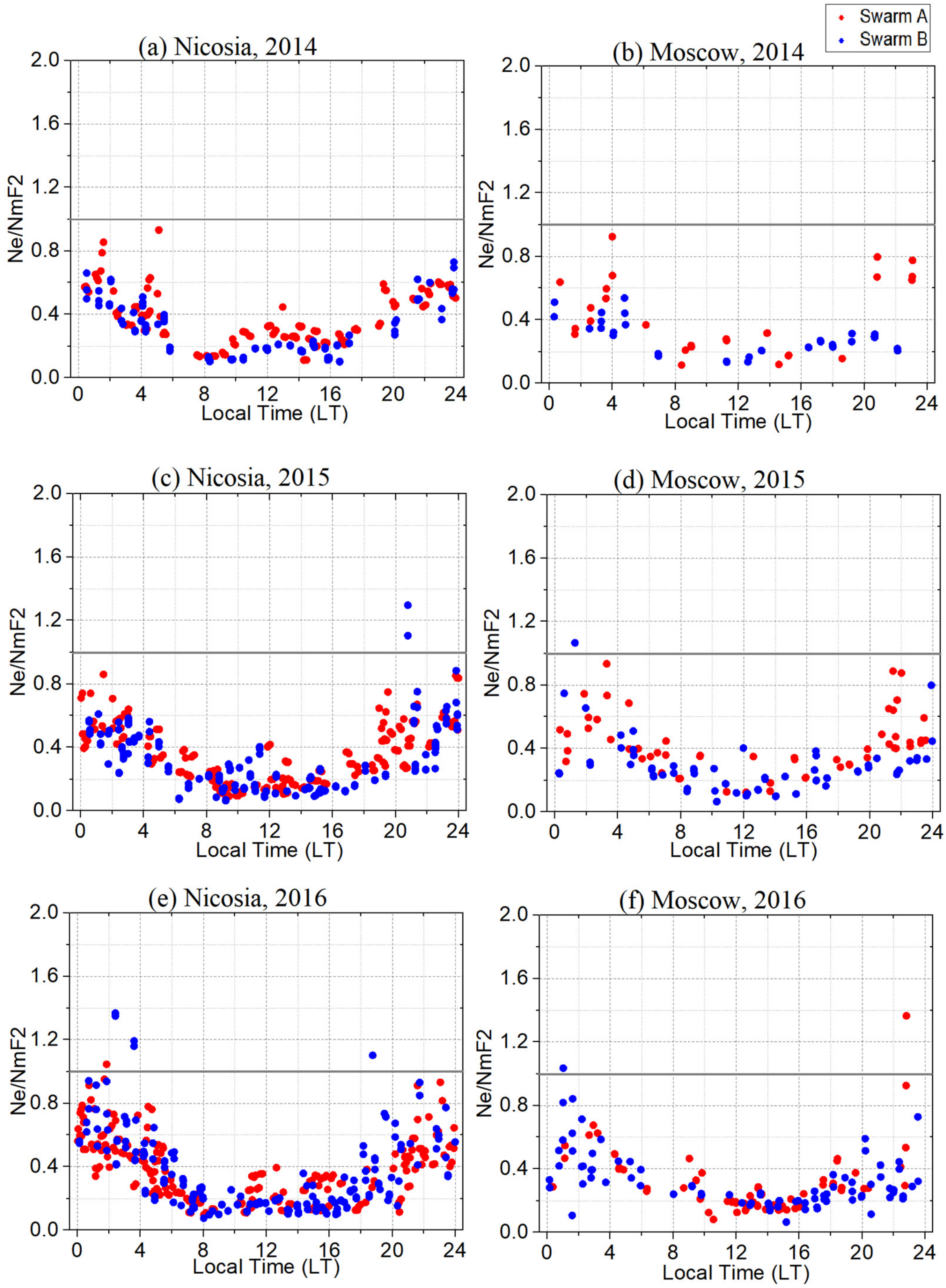


Figure 2. (**a**–**f**). Ne/NmF2 from Swarm A and B over Moscow and Nicosia for high-to-moderate solar activity during 2014 to 2016.

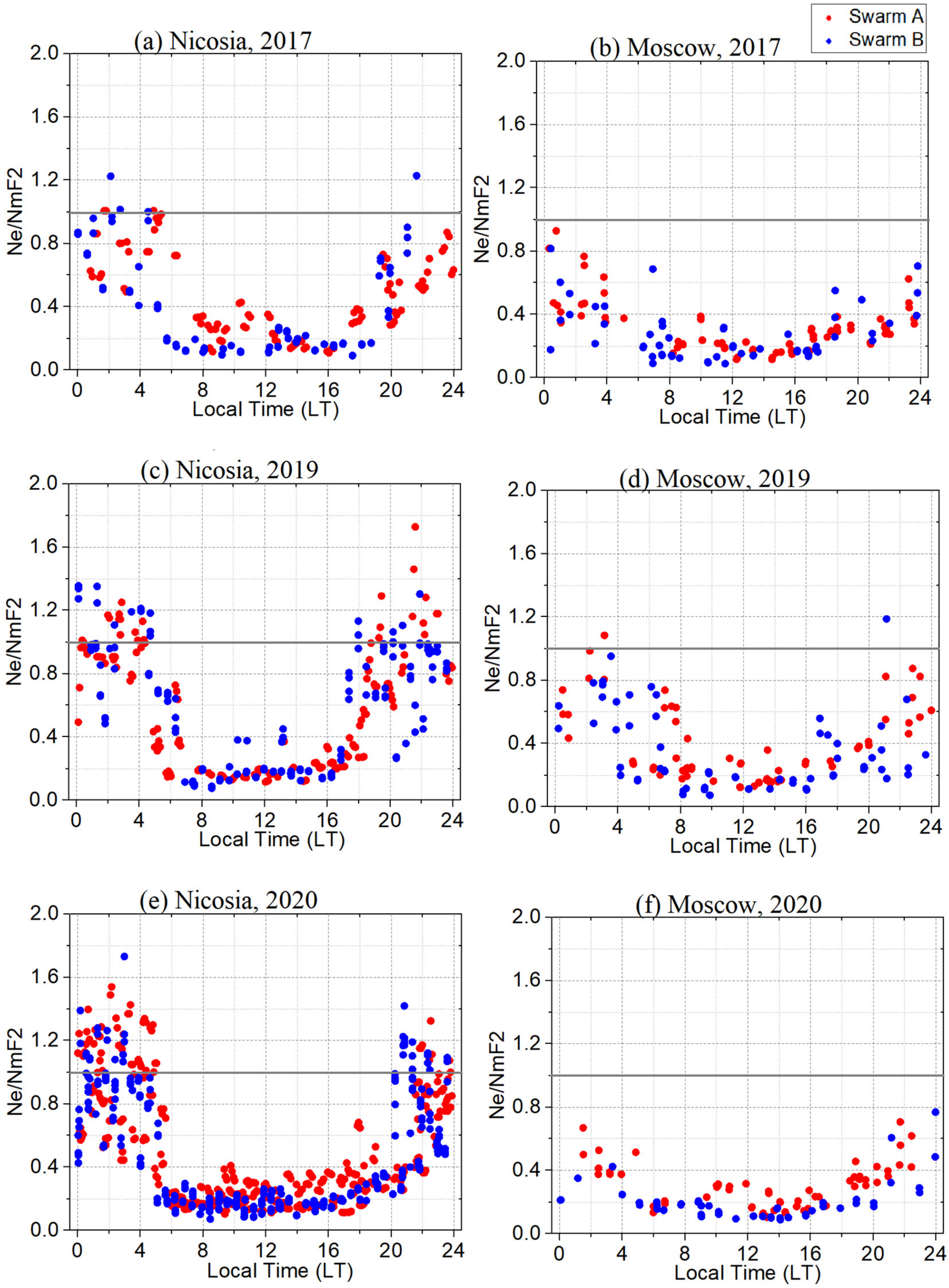


Figure 3. (**a**–**f**). Comparison of Ne/NmF2 from Swarm A and B over Moscow and Nicosia for moderate-to-low solar activity during 2017, 2019 and 2020.

Table 1. Percentage of observations for Ne/NmF2 $\geq$ 1 over Nicosia and Moscow.

Year	Nicosia		Moscow	
	Swarm A	**Swarm B**	**Swarm A**	**Swarm B**
2014	N.A.	N.A.	N.A.	N.A.
2015	N.A.	1.02%	N.A.	1.45%
2016	0.49%	2.51%	1.32%	1.16%
2017	2.06%	4.49%	N.A.	N.A.
2019	15.13%	12.5%	1.56%	1.54%
2020	14.05%	11.34%	N.A.	N.A.

In a comparison study of the Swarm plasma frequency with the corresponding measurements from the Incoherent Scatter Radar and COSMIC-1 performed by Lomidze et al. [15], the Swarm LP plasma frequency was lower by 9–11% with respect to the Incoherent Scatter Radar plasma frequency, although with a very high correlation (>0.98). For high COSMIC-1 plasma frequencies (>2.84 MHz), the Swarm LP plasma frequency underestimated the COSMIC-1 plasma frequencies by 9–11%, with a correlation coefficient of 0.97, while for lower COSMIC-1 plasma frequencies (<2.84 MHz), the Swarm plasma frequencies did not appear to be significantly lower than the corresponding COSMIC-1 values (by 0.1% for Swarm A, 1.5% for Swarm B and 3.8% for Swarm C), with lower correlation coefficients (0.83–0.86). The findings of that study are not in agreement with our results during the nighttime, probably because Lomidze et al. have used only 2000 collocated and coincident COSMIC-1 and Swarm observations in the period of December 2013 to June 2016 which correspond to high-to-moderate solar activity periods, as shown in Figure 3, for which not many extraordinary $Ne_{\_Swarm}$/NmF2 values (>1) are observed. Smirnov et al. [16] also compared the Swarm LP Ne observations with the coincident COSMIC-1 values and concluded on the $Ne_{\_Swarm}$ overestimation during the nighttime hours and the underestimation during the daytime. However, both studies were based on high-to-moderate solar activity datasets and neither Lomidze et al. nor Smirnov et al. considered the local time effect that is evident in our results. Larson et al. [17] compared the Swarm LP Ne with the coincident observations from the high-latitude Canadian ISR located at Resolute Bay between 2014 and 2019 and have concluded that the A-C $Ne_{\_Swarm}$ is actually lower than the ISR Ne by $\sim$30%, which actually contradicts what we observe on the basis of the IRI Ne estimations (green dots) when driven with the corresponding manually scaled peak parameters (NmF2-hmF2) under the preferred NeQuick topside option shown in Figures 4 and 5.

Finally, Liu et al. [18] have carried out a similar study in which they compared the coincident Ne measurements (in space and time) between the Swarm constellation and CSES satellite. They reported correlation coefficients exceeding 0.75 but electron density values of Swarm exceeding CSES Ne by a factor of 3–6.

To investigate how this effect is manifested on actual latitudinal electron density profiles, we selected such nighttime profiles for the low solar activity years of 2019–2020 that are depicted in Figures 4 and 5, with Swarm A (blue) and Swarm C (black) electron density values. On the same plots, we superimposed the actual NmF2 values (red) from the manually scaled ionograms over Nicosia, Moscow and Saint Petersburg around the same time as the satellite pass. In addition, as a reference, we have also included the corresponding topside electron density value at the altitude of the Swarm A and C satellite (505 km) generated by the IRI when driven with the corresponding manually scaled peak parameters (NmF2-hmF2) under the NeQuick topside option [11] which was the preferred option for IRI-2016, although additional modifications have been proposed [19] for the NeQuick topside formulation, and in IRI-2020, a new IRI topside option was also provided [20]. What is interesting to note is the fact that for almost all the 2019 profiles with the exception of case (Figure 4h), the measured NmF2 value (red) over Nicosia almost coincides with the measured topside Swarm A-C electron density latitudinal profile. The expected topside IRI value (green) is actually much lower. For most of these cases over

Moscow and Saint Petersburg, the difference between the measured NmF2 and IRI topside electron density values is much lower, and the IRI value coincides really well with the Swarm A-C electron density latitudinal profile with the exception of cases (Figure 4c,d). The same findings are more or less evident for the cases in 2020, in Figure 5. In fact, for the lowest solar activity cases of 2020, the measured NmF2 value (red) over Nicosia is even lower than the measured topside Swarm A-C electron density latitudinal profile, and an even higher discrepancy between the corresponding IRI topside electron density value and the Swarm A-C electron density latitudinal profile is evident.

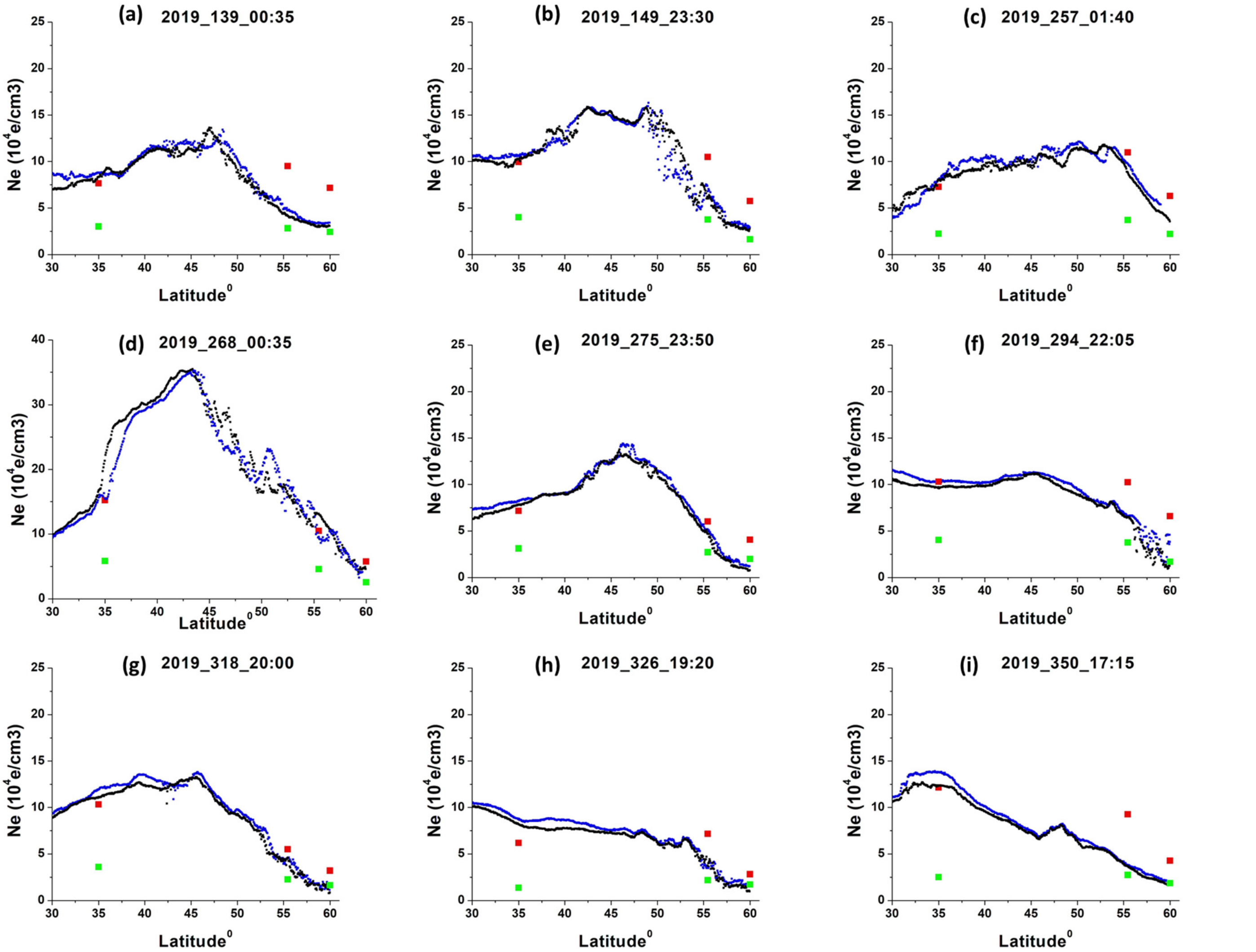


Figure 4. (**a**–**i**). The graphs show Swarm A (blue) and Swarm C (black) electron density traces with respect to the latitude with IRI-Ne values (green) and Digisonde NmF2 values (red) for the year 2019.

The excessive Ne_$_{\text{Swarm}}$ values could be due to the assumption considered in the LP processing algorithm that ionospheric plasma at Swarm altitudes is composed of O+ ions. While there is another approach in the Swarm constellation to measure the plasma Ne by a face-plate (FP) as a part of the TII instruments [21], the FP does not need such assumptions on the plasma. A validation study of the LP density measurements from Catapano et al. [21] has shown that the LP and FP measurements are very highly correlated in the daytime with a correlation coefficient of 0.98 and a moderate correlation of 0.47 during the nighttime, and a relative difference between the LP and FP is 19% and 34% for the daytime and nighttime, respectively. They have also reported that the LP measurements are more accurate during high solar activity as they record negative Ne values more frequently during low solar activity. It can be seen from Catapano et al. [22] that for lower values of

F10.7, a large number of invalid measurements have been recorded by the LP. In another study, Xiong et al. [23] underlined an underestimation of the Swarm LP Ne with respect to the corresponding FP Ne at high solar activity, the opposite effect at low solar activity and the verified FP Ne being more accurate by exploiting conjunctions over the Jicamarca ISR. Recently, Pignalberi et al. [24] successfully resolved the Swarm LP electron density overestimation during the nighttime for low solar activity by calibrating the Swarm B LP electron density observations through the FP observations from the same satellite.

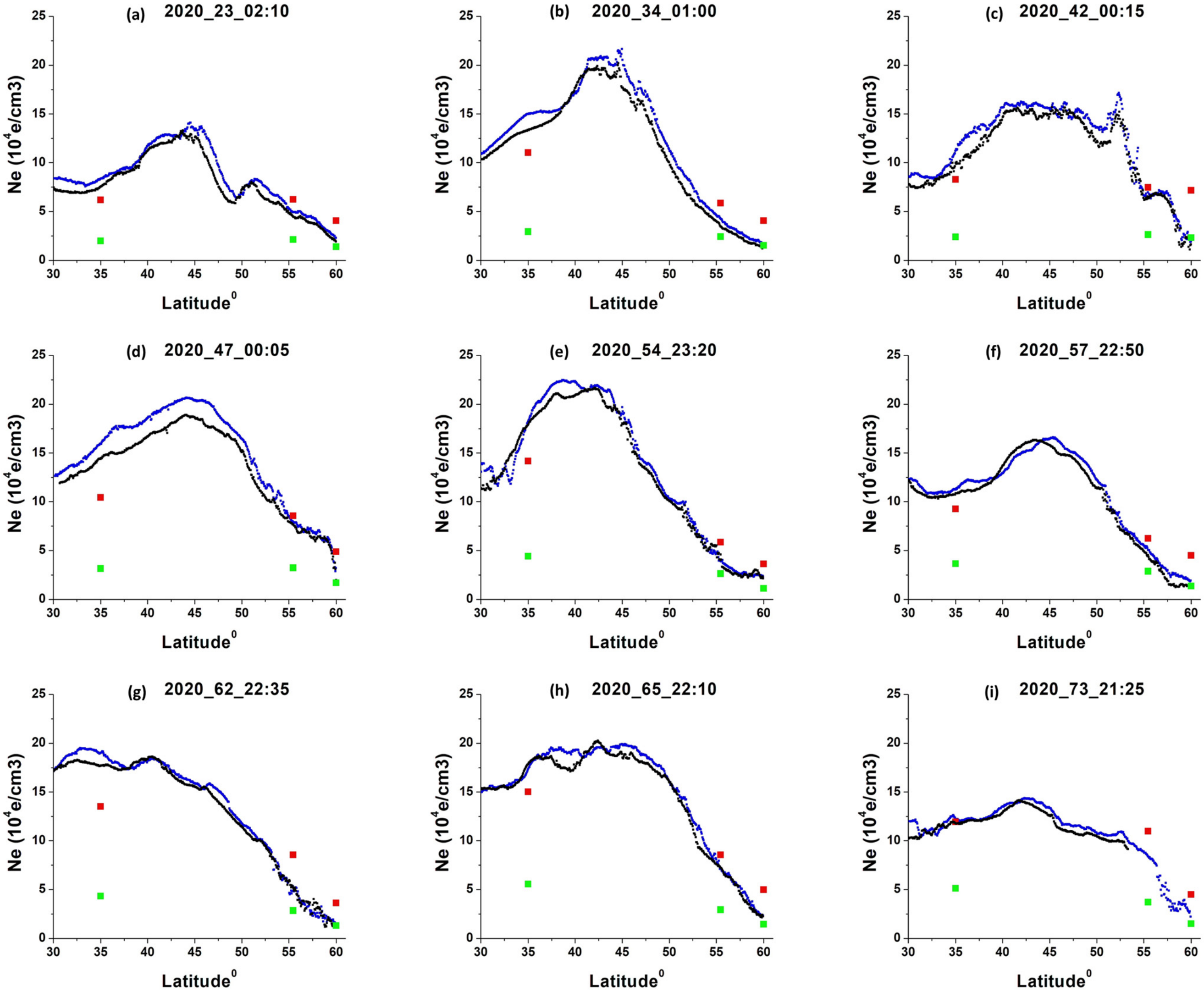


Figure 5. (**a**–**i**). The graphs show Swarm A (blue) and Swarm C (black) electron density traces with respect to latitude with IRI-Ne values (green) and Digisonde NmF2 values (red) for the year 2020.

Despite the fact that the IRI NeQuick topside option driven by manually scaled peak parameters (NmF2-hmF2) is expected to give a good approximation of the topside electron density value over a station, we decided to verify our results with an alternative topside measurement data source. That alternative topside dataset was provided by the COSMIC-1 mission. In particular, we have extracted the topside electron density values at the altitude of the Swarm B (505 km) from the radio occultation profiles over the three stations in the interval 2007–2018, during which the COSMIC-1 mission was active. We then calculated the Ne/NmF2 using both the Ne and NmF2 from the COSMIC-1 electron density profile. Figure 6 depicts the diurnal profile of this ratio for all the cases assembled over each station in 2007–2018 which cover the low, high and moderate solar activity periods. All three graphs verify that the Ne/NmF2 hardly exceeds a value of 0.5 under any solar activity level or time of day. This result further underlines the extraordinary $Ne_{\_Swarm}$ values during the nighttime over Nicosia, especially during the moderate-to-low solar activity years.

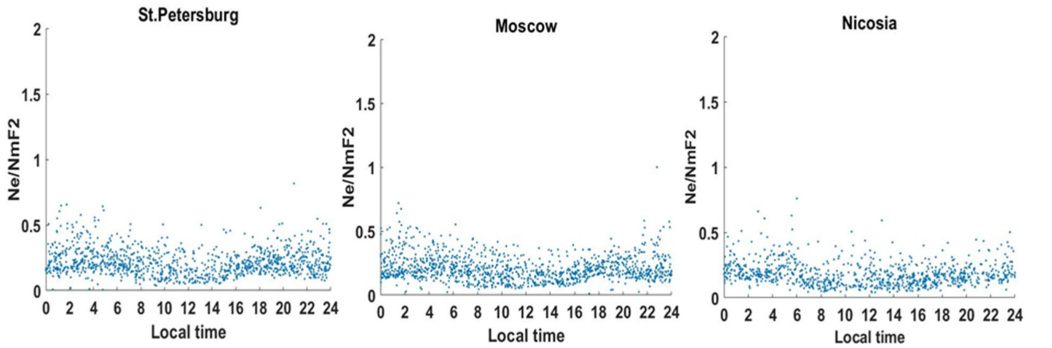


Figure 6. Local time variation in Ne/NmF2 of COSMIC-1 electron density (Ne) at Swarm B altitude (505 km) to COSMIC-1 peak electron density (NmF2) over St. Petersburg, Moscow and Nicosia for 2007–2018.

4. Conclusions

This long-term study investigated the ratio $Ne_{\_Swarm}/NmF2_{Digisonde}$ in the interval 2014–2020, encompassing a period of high-to-low solar activity within a narrow longitude sector in the vicinity of three Digisonde stations in Nicosia (35.14°N, 33.2°E), Moscow (55.5°N, 37.3°E) and Saint Petersburg (60.0°N, 30.7°E). Through solid evidence, we were able to establish its variation with the solar activity and time of day, as demonstrated in other studies, but also solidify the effect of latitude. The main finding is the extraordinary values of the $Ne_{\_Swarm}$ during the nighttime that are evident on the mid-latitude station of Nicosia. This is attributed to the inaccuracy in the LP measurement due to the assumption in the LP processing algorithm that at Swarm altitudes, the ionospheric plasma is composed only of O+ ions. By focusing on a specific longitude sector, we were able to focus on the effect of the latitude on this inaccuracy. Based on these results, we plan to extend this investigation over more Digisonde stations at different sectors in the near future, in an effort to establish if and how these extraordinary values of the Ne_{Swarm} are manifested in other longitude sectors.

Author Contributions: Conceptualization, H.H.; methodology, H.H.; formal analysis, A.K.S., K.S.P.; investigation, A.K.S., H.H.; data curation, T.G., H.H.; writing—original draft preparation, H.H.; writing—review and editing, K.S.P., H.H.; visualization, A.K.S.; supervision, H.H.; project administration, H.H.; funding acquisition, T.G., H.H. All authors have read and agreed to the published version of the manuscript.

Funding: This paper is funded by the project "Retrospective modelling and prediction of Ionospheric weather" BILATERAL/RUSSIA (RFBR)/1118/0004 which is co-funded by the Republic of Cyprus and the European Regional Development Fund (through the "Bilateral Collaborations" RESTART 2016–2020 Programme for Research, Technological Development and Innovation).

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank the Lowell GIRO Data Center (LGDC) (http://spase.info/SMWG/Observatory/GIRO, accessed on 2 September 2022) and Digital Ionogram Data Base or DIDBase (https://lgdc.uml.edu/common/DIDBStationList, accessed on 2 September 2022) for providing ionograms over Saint Petersburg and the European Space Agency (ESA) for making Swarm data publicly available via ftp://swarmdiss.eo.esa.int, accessed on 2 September 2022.

Conflicts of Interest: The authors declare no conflict of interest.

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