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**3D INVESTIGATION INTO THE ORIGIN OF MID-LATITUDE SCINTILLATION
AND ITS EFFECT ON TRANS-IONOSPHERIC RADIO SIGNALS (UHF)**

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TRANS-IONOSPHERIC RADIO SIGNALS (UHF)**

June 4, 2022

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Abstract:

The stated broad research title was pursued under the following five subtopics:

In the first subtopic, we analyzed the occurrence of ionospheric irregularities over South Korea and Japan (mid-latitudes) during the years 2010 - 2015. The irregularities were quantified using the rate of change of total electron content (TEC) index (ROTI), which detects irregularities with scale sizes in the range of 400m – 2.5km. The ROTI threshold for an ionospheric irregularity to have occurred was set as 0.1 TECU/min. Results showed that ionospheric irregularities mostly occur during night-time and around local noon-time in the seasons of spring and summer. In addition, the percentage of ionospheric irregularities had a high positive correlation with solar flux (F10.7) ($r > 0.72$). For the first time, we showed good correspondence between ionospheric irregularities measured by the ROTI index and sporadic E (Es). The median ROTI associated with ionospheric irregularities over a South Korea station (DAEJ) and a Japan station (KGNI) were 0.131 and 0.125 TECU/min, respectively. However, in severe cases of ionospheric irregularities, the ROTI values over DAEJ (KGNI) can reach 0.246 (0.217) and 0.314 (0.339) TECU/min during day and night,

respectively. These critical ROTI values can be important in interpreting and monitoring ionospheric irregularity occurrence over South Korea and Japan. This work has been successfully published in *Advances in Space Research*.

In the second subtopic, we developed a model of Total Electron Content (TEC) over the African region. The TEC data were obtained from radio occultation measurements done by the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) satellites. Data during geomagnetically quiet time ($K_p < 3$ and $Dst > -20$ nT) for the years 2008 - 2011, and 2013 – 2017 were binned according to local time, seasons, solar flux level, geographic longitude and latitude. B splines were fitted to the binned data to obtain model coefficients. The model was validated using actual COSMIC TEC data of the years 2012 and 2018. The validation exercise revealed that, approximation of observed TEC data by our model produces root mean squared error of 5.02 TECU. Moreover, the modeled TEC data correlated highly with the observed TEC data ($r = 0.93$). Due to the extensive input data and the applied modeling technique, we were able to reproduce the well-known TEC features such as local time, seasonal, solar activity cycle, and spatial variations over the African region. Further validation of our model using TEC measured by ionosonde stations over South Africa at Hermanus, Grahamstown and Louisville revealed r values > 0.92 and RMSE < 5.56 TECU. These validation results imply that our model can estimate fairly well TEC that would be measured by ionosondes over locations which do not have the instrument. Another importance of this study is the fact that it has shown the potential of using basis spline functions for modeling ionospheric parameters such as TEC over the entire African region. This work has been successfully published in *Annales in Geophysicae*.

In the third subtopic, we investigated ionospheric disturbances caused by the North Korean rocket (Hwasung-15) using a four-dimensional variational (4D-Var) data-assimilation model. The four-dimensional variational (4D-VAR) technique, originally developed for weather forecasting applications, has been utilized in a data-assimilated model to estimate rocket exhaust emission from observed ionospheric disturbances. In this study, we improved the 4D-VAR method by utilizing a more realistic chemical model in the ionosphere and applied it to characterize ionosphere disturbances caused by the Hwasung-15 (H-15) rocket exhaust chemicals. The H-15 rocket was launched southeastward from North Korea at 18:17 UT on 28 November 2017. During the first hours of the launch, the total electron content (TEC) derived from the Korean ground-based GNSS receiver network exhibited ionospheric disturbances along the Rocket's trajectory. The disturbances were most distinct along the GLONASS (Global Orbiting Navigational Satellite System) line of site. By assimilating the measured TEC data into the 4D-VAR model, we were able to characterize the ionospheric depletion and recovery with respect to the standard ionospheric model, IRI-2016. In addition, the rocket exhaust emissions were estimated to be $\sim 1.5 \times 10^{27}$ molecules per sec, with a number ratio of 2:1 for water to hydrogen in the rocket's exhaust gas. This work has been published in *Journal of the Korean Physical Society*.

In the fourth subtopic, we carried out a regional ionospheric assimilation study with GPS and COSMIC measurements using a 3D-var algorithm (IDA4D). The Ionospheric Data Assimilation Four-Dimension (IDA4D) is, developed by Bust et al. (2007), a continuous time and three-dimension variational (3D-Var) algorithm that can optimally estimate the ionosphere from a model and measured data. In this study, we utilized three different data types into IDA4D for a regional ionosphere estimation: slant total electron contents (STEC) obtained from a Global Positioning System (GPS) network, NmF2 (peak electron density of the F2 layer) and STEC from Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) satellite. These multiple type data were assimilated into a background model, the International Reference Ionosphere (IRI – 2016). To evaluate the effect of each data type, the assimilation was performed on the following data combinations (cases): (1) GPS-STEC's only; (2) GPS-STEC's and NmF20s from COSMIC; (3) GPS-STEC's and COSMIC-STEC's; and (4) all three data types. For each case computed foF20s (F2 layer critical frequency) from IDA4D were compared with measured values from five ionosondes (I-Cheon, Jeju, Okinawa, Kokubunji, and Wakkanai) in the region of Korea and vicinities for the test periods of March, June, September and December in 2015. The comparison shows that computed foF20s for all cases have higher correlation coefficients (CC) and less root mean square errors (RMSE) from measured values than IRI estimated values. In Cases 2, 3 and 4, IDA4D performance progressively improved in areas where GPS measurements were not covered but COSMIC STEC and NmF2 data were available. Furthermore, the IDA4D assimilation yields better results for electron density profiles and TEC values in comparison with observed values than the IRI model does. Thus, our study suggests that the IDA4D model with multiple data types can provide a reliable estimation of the regional ionosphere over the Korean Peninsula and vicinities. This work has been published in *Advances in Space Research*.

In the fifth subtopic, we investigated the latitudinal distribution of ionospheric irregularities over the northern hemisphere along 120 – 130° E longitude sector. The study used 7 ground-based GPS receivers located along magnetic latitude ranging from 10.3 – 65.7° N. In addition, the study used observations of GPS receivers onboard the Swarm satellites during the passes of the satellite over the region under study. Observations during geomagnetically quiet days ($K_p \leq 3$) of the years 2014 – 2017 were used. The total electron content (TEC) derived from observations of the GPS receivers were used to compute the rate of change of TEC (ROT) to represent ionospheric irregularities. For the first time, we noticed that the speed of the Swarm satellite appears to have a multiplying effect on the ROT data observed by the receiver on the satellite. In this study, the ionospheric irregularities were classified into levels of low ($ROT < 0.5$ TECU/min), moderate ($0.5 \leq ROT < 1$), high ($1 \leq ROT < 2$), and extreme ($ROT \geq 2$). The latitudinal distribution of high – extreme ionospheric irregularities depicted concentrations around geographic latitude ranges, 1 – 4° N (mag lat. -10.8 – -9° N), 9 – 34° N (mag lat 7.8 – 28.3° N), and 62.5 – 84° N (mag lat. 57.1 – 77.4° N).

Our results also revealed that low latitude high-extreme ionospheric irregularities during the day can extend in pole-ward direction up to geographic latitude 34° N (mag lat. 28.3° N). Over high latitudes, high - extreme ionospheric irregularities during the day and at night can extend in equator-ward direction to geographic latitudes 74° N (mag lat. 68.3° N) and 62.5° N (mag lat. 57.1° N), respectively. The general trend seems to show that as the solar flux level reduces the percentage of moderate – extreme occurrence of ionospheric irregularities also reduces. However, the reduction of solar flux level may not completely eliminate occurrence of low latitude medium – extreme irregularities. The results may guide future development of empirical ionospheric irregularity occurrence model over the region.

The detailed description of the five subtopics that we have carried out during the entire project period of 2019-2022 is presented below.

I. Observations of ionospheric irregularities and its correspondence with sporadic E occurrence over South Korea and Japan

1. Introduction

The Earth's ionosphere often becomes turbulent and develops electron density irregularities, commonly known as ionospheric irregularities. Basu et al. (2002) stated that ionospheric irregularities scatter radio waves; causing amplitude and phase scintillation which in turn affect satellite communication and navigation systems. These effects are most intense in the equatorial region, moderate at high latitudes and minimum at middle latitudes. As such, most literature about ionospheric irregularities is biased towards the low latitude regions, with either little or inadequate information over the mid-latitudes. The most common occurrence of ionospheric irregularities over mid-latitudes might be associated with medium-scale traveling ionospheric disturbances (MSTIDs) and sporadic E (Es) (e.g., Ecklund et al., 1981; Pignalberi et al., 2014; Hernández-Pajares et al., 2006; Yamamoto et al., 1991; and Saito et al., 2007). According to Hunsucker (1982), MSTIDs are ionospheric manifestations of gravity waves within the ionosphere acting principally as a passive tracer to display the motions of the neutral atmosphere. In this study, we focused on establishing the correspondence between ionospheric irregularities and Es occurrence at the mid-latitudes.

The Es-layer is a densely ionized E region lying at an altitude range of about 90 - 120 km (Schunk and Naggy, 2009; Rishbeth and Garriott, 1969). Its occurrence over the mid-latitude is usually attributed to the plasma convergence effect of the neutral wind shear (Mathews, 1998). The mid-latitude Es does occur often, with maximum frequencies near midday and summer (Whitehead, 1970). For example, Atulkar et al. (2016) analyzed the Es critical frequency (f_oEs), blanketing frequency (f_bEs), and minimum virtual height ($h'Es$) retrieved from ground based ionosonde at Yamagawa, Japan; the parameters were found to reach maximum between 08:00 local time (LT) and local noon, and minimum after sunrise and two hours before the sunset. In addition, the highest values of f_bEs , f_oEs and $h'Es$ were recorded during the summer season while the lowest values were recorded during the months of autumn. Also, a study by Haldoupis et al. (2007) showed that both the f_oEs , and the meteoric influx follow a similar seasonal dependence marked by a strong summer maximum.

According to Yamamoto et al. (1991), the mid-latitude E-region field-aligned ionospheric irregularities are closely associated with Es, whose intense occurrence can lead to scintillation of microwaves (especially, signals of the Global Navigation Satellite System (GNSS)) (Maeda and Heki, 2014). Further, field-aligned super plasma bubble was observed over East Asian mid-latitude region during February 12, 2000 geomagnetic storm (e.g., Ma and Maruyama, 2006). During the same period, GPS (Global Positioning System) receivers

were found to experience loss of lock.

In this study, we analyzed GPS signals over South Korea and Japan during the years 2010 – 2015 with the aim of establishing the critical values of the rate of change of Total Electron Content (TEC) index (ROTI) used to study the irregularities. Furthermore, we aimed at establishing the correspondence between occurrences of irregularities (ROTI) and Es. The correspondence between ionospheric irregularities (high ROTI) and MSTIDs and field-aligned irregularities were also discussed.

2. Data sources and methods of analysis

This study used observations from ground-based GPS-receivers located at Daejeon (DAEJ), South Korea, and Koganei (KGNI), Japan. The observations are stored in Receiver Independent Exchange data (RINEX) format files and can be accessed from the website of the University NAVSTAR consortium (UNAVCO) via the link, <ftp://data-out.unavco.org>.

Table 1: Ionosonde and GPS receiver stations used in the study

Location	ID	Country	Geog lat (°)	Geog lon (°)	mag lat (°)
Daejeon	DAEJ	S. Korea	36.40	127.37	30.62
Kokubunji	TO536	Japan	35.70	139.50	29.45
Koganei	KGNI	Japan	35.71	139.49	29.46
Icheon	IC437	S. Korea	37.10	127.50	31.32

Table 1 provides detailed information about the locations of the GPS receivers as well as the ionosonde stations (Kokubunji (TO536) and Icheon (IC437)) used in this study. The RINEX files obtained from the GPS receiver stations were processed using GPS-TEC (total electron content) analysis software (Seemala and Valladares, 2011) to obtain slant TEC (STEC) as a function of Universal Time (UT) at 30-seconds resolution and elevation angles of satellites tracked. After removing satellite and receiver biases from STEC, the software maps it to vertical TEC (VTEC) at the ionospheric pierce points located at 350 km altitude. The satellite biases are published by the University of Berne in Switzerland (<ftp://ftp.unibe.ch/aiub/CODE/>). It is important to mention that the satellites are usually identified by pseudo-random numbers (PRNs). The GPS-TEC analysis software estimates receiver bias for a specific receiver by trying several values and taking the one that gives the minimum summed standard deviation of observed VTEC during 03:00 - 06:00 LT. To minimize multipath effects, we only considered STEC values observed at elevation angles greater than 30°.

The ionospheric irregularities cause phase fluctuations in GPS signals which can be quantified using the rate of change of TEC (ROT) (Aarons et al., 1996; Pi et al., 1997). According to Wanninger (1993), time series of ROT provides an excellent means to detect phase scintillations due to MSTIDs. Phase scintillations at frequencies much lower than the Fresnel frequency occur when optical path changes of a radio wave take place due to the presence of irregularities with scale-sizes that are much larger than the scale-size of the first

Fresnel zone (Pi et al., 1997). On the other hand, when the irregularity scale-sizes are comparable or smaller than the first Fresnel zone, diffraction effects and scattering of a radio wave can cause amplitude and phase scintillation at frequencies higher than the Fresnel frequency. For the case of GPS signals at E- and F-regions, the Fresnel frequency and the scale size of the first Fresnel zone ranges are 0.08 – 0.36 Hz and 145 – 310 km, respectively (Pi et al., 1997). Several studies have used the ROT and ROT index (ROTI) to study ionospheric irregularities with scale sizes ranging from ~0.4 to 2.5 km which are far less than the quoted scale size of the first Fresnel zone in E- and F-regions (Aarons et al., 1996; Pi et al., 1997; Zou and Wang, 2009; and Wanninger, 1993). To identify and statistically present the irregularities with these scale sizes, Pi et al. (1997) defined the ROTI by taking the standard deviation of ROT over a 5-min period. A similar procedure was also followed in this study. Specifically, the STEC values were used to compute the ROT. The ROTI values were in turn computed from ROT values during the years 2010 – 2015.

Simultaneous observations of ROTI over KGNI and foEs parameter measured by the ionosonde located at Kokubunji (TO536), Japan, during the years 2010 - 2015 were analyzed to reveal the correspondence between the two parameters. The foEs data can be accessed from the National Oceanic and Atmospheric Administration (NOAA) website via the link, <ftp://ftp.ngdc.noaa.gov>. The longitude and latitude separation of TO536 and KGNI are less than 0.01°, as indicated in Table 1. The small separation of the stations may increase chances of signals observed by the GPS receiver crossing the ionosphere directly over the ionosonde station, giving assurance that the high values of ROTI observed by the GPS receiver may likely be due to Es detected by the ionosonde. Due to lack of nearby ionosonde station at DAEJ, the correspondence between ionospheric irregularities and foEs was only established over KGNI. Later in section 3.2, we showed that the foEs values observed over TO536 are mostly greater than those over Icheon (IC437), South Korea. Table 2 presents the number of days with data over KGNI, DAEJ, and TO536 during the period considered in this study.

Table 2: Number of days with data used during the years 2010 - 2015

Station Code	2010	2011	2012	2013	2014	2015
	Number of days					
KGNI	314	274	166	273	270	303
TO536	271	238	249	253	239	270
DAEJ	332	349	327	305	299	342

3. Results and discussions

3.1. Seasonal occurrence of ionospheric irregularities

In Figure 1, panels of columns (i) and (ii) present the ROTI values corresponding to the various satellites in view of the receiver at DAEJ and KGNI, respectively. Panels in rows (a) – (f) present the variation of ROTI as a function of months during the years 2010 – 2015,

respectively. The red lines in Figure 1 indicate the background ROTI (*BGR*) value that was obtained using the expression

$$BGR = MROTI + 3 \times STD, \quad (1)$$

where *MROTI* and *STD* are the median and standard deviation of the ROTI values within the study period, respectively. Since frequency of ionospheric irregularities over mid-latitude regions are expected to be generally low, fairly high error term ($3 \times STD$) was added to *MROTI* in order to obtain high *BGR* value. When such a value of *BGR* is applied to filter ROTI data (e.g., by discarding ROTI values $< BGR$), mostly high ROTI values may remain and they may correspond to strong phase fluctuations or steep spatial gradients in TEC (ionospheric irregularities). As discussed in the next paragraph, some of the ionospheric irregularities are associated with phenomena such as Es, field-aligned irregularities, and MSTIDs. In this study we refer to ROTI values that exceed the *BGR* value as ionospheric irregularity or irregularity occurrence. The *BGR* values over DAEJ and KGNI were 0.092 and 0.115 TECU/min, respectively. These *BGR* values are comparable to those in a study by Ma and Maruyama (2006), wherein, ionospheric irregularities were considered to have occurred when $ROTI > 0.1$ TECU/min.

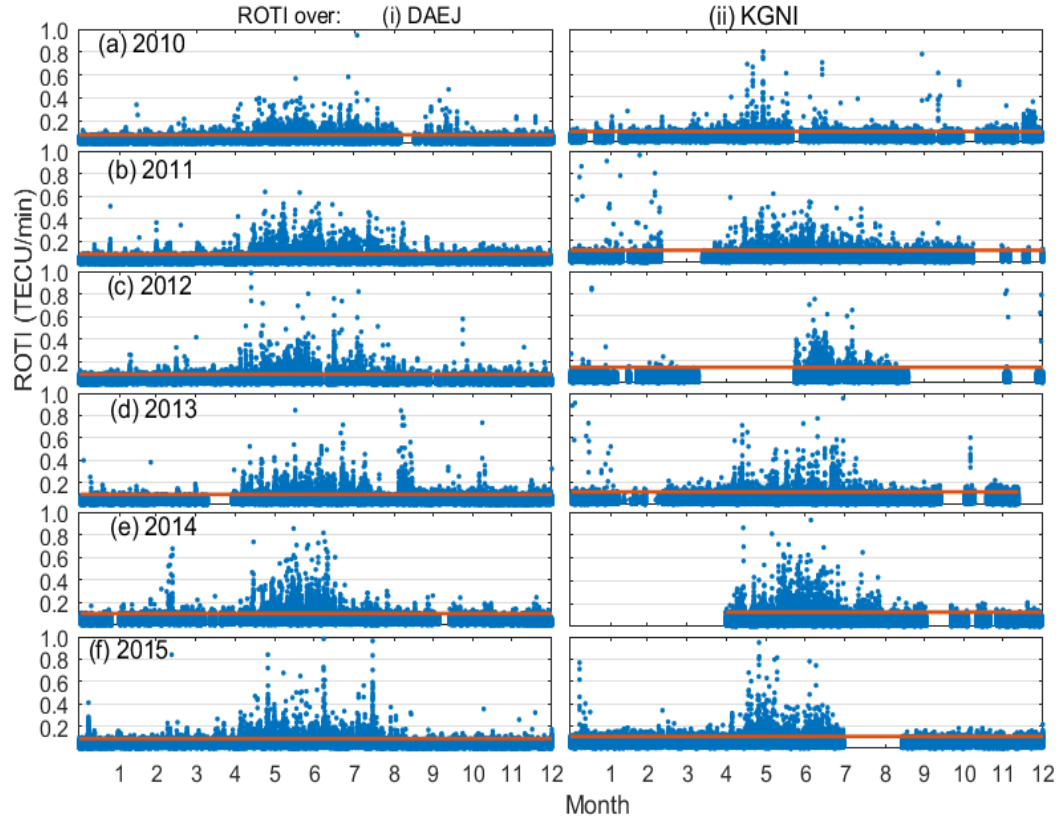


Figure 1: ROTI observations over (i) DAEJ and (ii) KGNI. Panels in rows (a) - (f) are for the years 2010 - 2015, respectively. The red line indicates the background ROTI.

Figure 1 depicts that ionospheric irregularities occur almost throughout the year. However, the dominant occurrences of ionospheric irregularities appear to be at the end of spring (May) and in summer months (June – August). To illustrate that this pattern is similar to that of Es occurrence, we present superimposed graphs in Figure 2 of daily percentages of irregularities (*PoI*) (blue line) and maximum foEs values (red line) over KGNI and TO536, respectively. As mentioned before, KGNI and TO536 are co-located. The *PoI* in a particular day was determined using the expression,

$$PoI = \frac{\text{number of ROTI values} > BGR}{\text{Total number of observed ROTI}} \times 100 \quad (2)$$

The results for the years 2010 -2015 are presented in Figures 2 (a) – (f) respectively. Indeed, the figure shows that both *PoI* and foEs values have high values dominantly in the summer months. Considering that the mid-latitude Es-layers form when metallic ions of meteoric origin in the lower thermosphere are converged vertically in a wind shear, the foEs values which are dominantly high in summer might be attributed to the fact that meteoric influx has maximum occurrence in summer (Haldoupis, 2007). Schunk and Naggy (2009) stated that neutral metal atoms are created during meteor ablation, and their subsequent ionization (to form metallic ions such as Fe⁺ and Mg⁺) via photo-ionization and charge exchange yields the long-lived metallic ions. The position of the sun in summer which is almost at zenith plays important role in the creation of the metallic ions through photo-ionization. Since some of the high ROTI values are suspected to be associated with Es, it is expected that high *PoI* also occurs dominantly in summer months.

Therefore, it may be suggested that the high values of ROTI in summer months are detections of irregularities associated with Es: irregularities within Es-layer can scatter radio waves if their dimensions are comparable to half a radio wavelength, and at times they may produce scintillation of trans-ionospheric signals (Hargreaves, 1991). Yamamoto et al. (1991) reported on mid-latitude E-region field-aligned irregularities over Shigaraki, Japan during periods after sunset and sunrise. They stated that the irregularities during post-sunrise period are distributed below 100 km altitude, while irregularities during the post-sunset period appear above 100 km altitude. The authors also inferred that the irregularities are probably produced by the gradient drift instability acting on electron density gradients related to Es-layer. This inference was based on the works of Ecklund et al. (1981) which found that the 3-m scale size E-region irregularities occur when intense Es patches are known to occur. Ecklund et al. (1981) further mentioned that gradient drift irregularities are generated when

electrons drift horizontally under the influence of an electric field component parallel to the vertical electron density gradient. In fact, Basu et al. (1978) showed that between sunset and midnight, 3 m scale irregularities that backscatter radar signals at 50 MHz, co-exist with $\sim 0.1 - 1$ km scale irregularities that cause VHF and L-band scintillations. Therefore, in addition to the 3 m scale size irregularities within the Es-layer, there might be irregularities with scale sizes in the range of 0.4 – 2.5 km, as previous studies suggested. We make this tentative assumption because in our results, ROTI is defined to measure irregularities with a scale size range of 0.4 – 2.5 km, and its variation is similar to that of Es. More specifically, the variations of irregularity occurrence similar to that of Es are those with seasons (Figures 1, 2, and 4), local time (Figure 7), and spatiality (Figure 5).

Moreover, a number of studies have suggested that irregularities detectable at GPS microwave frequencies generally occur at high altitudes (in the F-region) but might be seeded by low-altitude instabilities in E-region. For example, according to Rishbeth and Garriott (1969), the small-scale electron density irregularities that seem to exist at every level in the ionosphere are superimposed on the background electron density and at around 100 km, turbulent air motions might produce irregularities. This might establish an irregular pattern of electric fields, which could cause irregular drifts at greater heights where the plasma is not directly influenced by air motion. Another evidence for electron density irregularities within Es-layer structures was presented by Maruyama et al. (2006). They found that during very high frequency (VHF) quasi-periodic backscatter echoes, foEs increased while fbEs decreased, so that the difference between the two parameters was enhanced, indicating the development of strong spatial structuring in electron density within the Es-layer. Yokoyama and Stolle (2016) stated that the sharp plasma density gradient associated with inhomogeneous Es-layer tends to be unstable owing to neutral wind shears and polarization electric fields which map onto the magnetic field lines leading to a coupling between the E- and F-regions.

Later in section 3.3, we show that most of the irregularities depicted in Figures 1 and 2 occur during post-sunrise and sunset, similar to that reported by Yamamoto et al. (1991). Because of this similarity, we assume irregularities observed in this study are located just below (after sunrise) and (after sunset) above 100 km. The irregularities below 100 km may be associated with Es while those above may be associated with MSTIDs. The suggestion that irregularities above 100 km may be associated with MSTIDs is premised on the relationship of MSTIDs with the F2 region (Ssessanga et al., 2017). It is important to note that previous results show that MSTIDs frequently occur at night in summer months (Ding et al., 2011 and Chen et al., 2019), similar to irregularity occurrence in summer months and at night as depicted in our Figures 1, 2, 4 and 7.

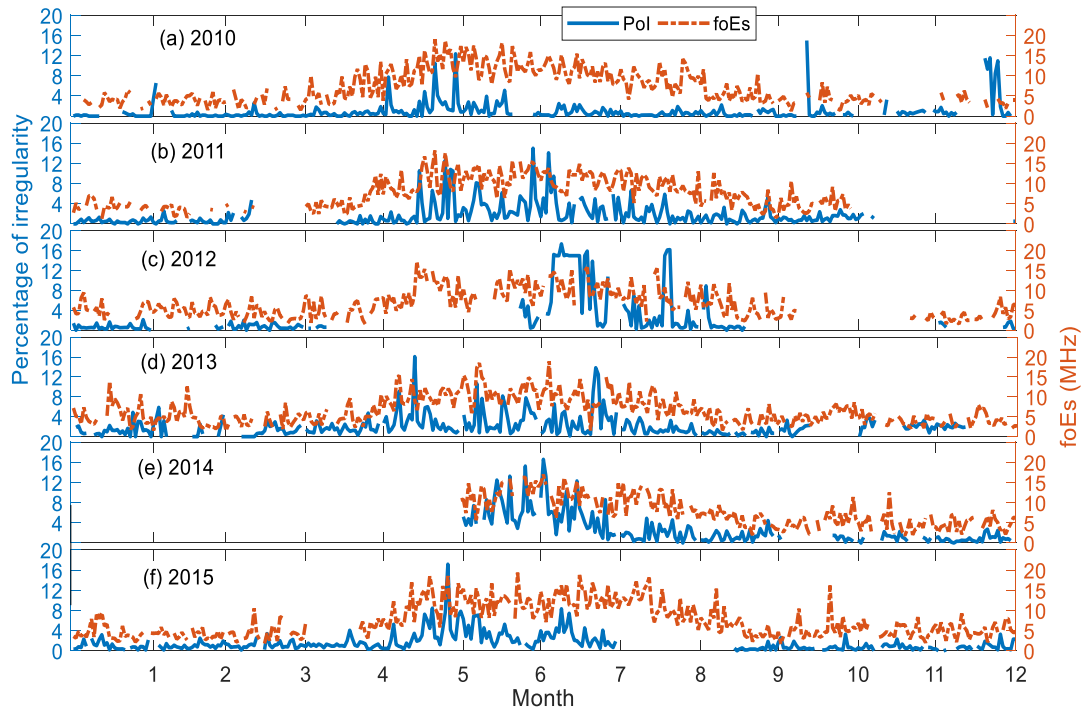


Figure 2: The blue and red lines present daily *Pol* over KGNI and maximum *foEs* values over TO536, respectively. Panels (a) - (f) are for the years 2010 - 2015, respectively.

It can also be observed from Figure 2 that there are cases where high *Pol* are observed and yet the corresponding *foEs* values are low. This observation may be attributed to the geometry of the measurements. Although the ionosonde station and the GPS receiver are nearly co-located, the *foEs* observations are directly over the ionosonde while the line of sight between the receiver and the satellite may not necessarily pass directly over the ionosonde. Therefore, the ionospheric irregularities may be along directions that are not over the ionosonde station. If the irregularity occurrences are due to an F-region phenomenon (such as MSTIDs) within the vicinity of the GPS receiver, high *Pol* may also be observed simultaneously with low *foEs* values.

There are also many cases in Figure 2 that depict high *foEs* coincident with low *Pol*. This may be explained in terms of the geometry of observation and scale size of the irregularity: If the plasma instability is not along the line between the receiver and GPS satellite, the irregularities will not be detected as high *Pol*. In addition, when the high *foEs* is associated with irregularities that have scale sizes outside the range of ~400 m – 2.5 km, the *Pol* may not be detected to be large. Furthermore, *BGR* is mainly dominated by the F-region high densities, and any perturbation in these densities can easily shadow out the Es signatures in ROTI, resulting in low *Pol*.

The isolated few cases of high *Pol* (see Figure 2 (a) in October and December) and *foEs* (see Figure 2 (d) in January, (e) in November, and (f) in October) in other seasons needs

further investigation.

Figure 3 clearly demonstrates a case where increased foEs values appear to coincide with occurrences of increased ROTI values. In the figure, panels (a) and (c) present ROTI over KGNU and the elevation angles of the associated PRNs, respectively, while panel (b) presents foEs over TO536. The data presented in Figure 3 were for June 23, 2012.

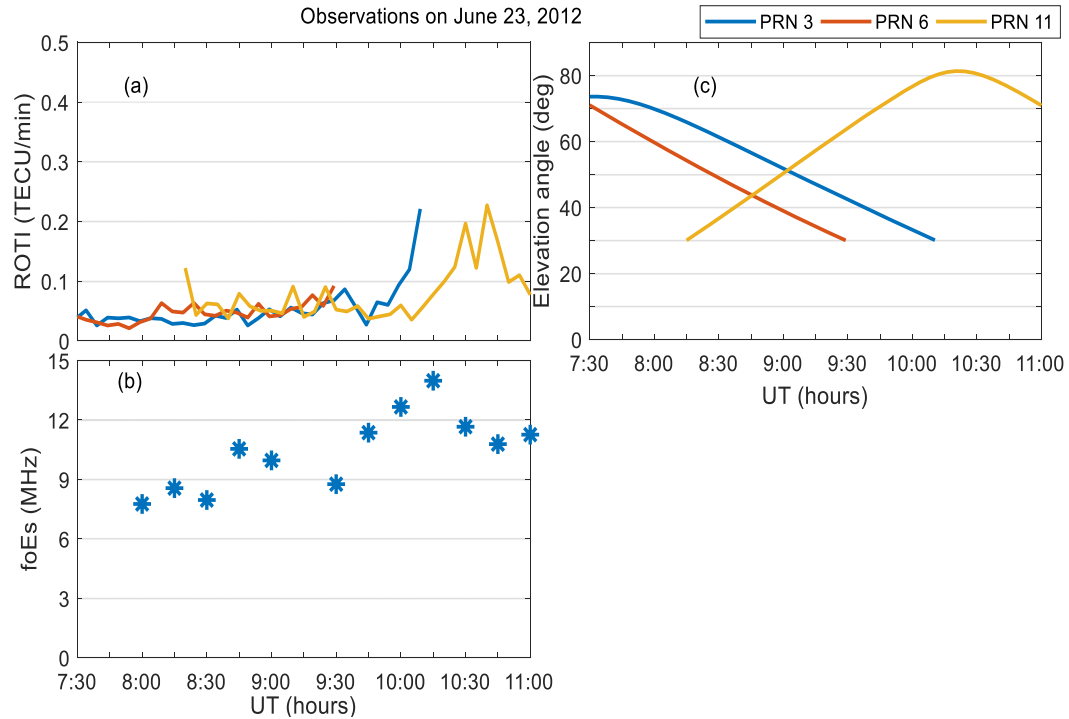


Figure 3: Panels (a) and (c) show ROTI over KGNU and the elevation angles of the associated PRNs, respectively, while panel (b) shows foEs over TO536. The observations presented were for June 23, 2012. The blue, red and yellow colors (in panels (a) and (c)) represent data of PRNs 3, 6, and 11, respectively.

It can be seen in Figure 3 that at around 10:15 UT when foEs peak appears to occur, PRNs 3 and 11 depict ROTI values >0.1 TECU/min. At around the same time, the elevation angle of PRN 11 was very high ($>70^\circ$), giving assurance that the irregularities detected by it might be due Es event over TO536. These discussions might support the claim that occurrences of Es may result into ionospheric irregularities which are observed as high ROTI values.

3.2. Dependence of ionospheric irregularities on geomagnetic and solar activities

During geomagnetic storms, the mid-latitude region may experience either negative or positive ionospheric responses, due to changes in neutral composition, expansion of the Equatorial Ionization Anomaly (EIA), penetration electric fields, and large-scale traveling ionospheric disturbances (e.g., Matamba et al., 2016 and Mansilla, 2004). Under such perturbed conditions, the occurrence of ionospheric irregularities may also be affected since

their formation depends on the state of the background electron densities. An exhaustive discussion on all factors that lead to the modification of the background electron densities and how they affect ionospheric irregularities is out of scope for this current study. Rather, here, we mention and briefly discuss the relationship between Es (a candidate for ionospheric irregularities) and geomagnetic activity. Drawing parallels in this relationship is still debatable since some studies report good (e.g., Whitehead, 1970) while others report weak or no correlation (e.g., Rishbeth and Garriott, 1969) between Es and geomagnetic activity.

In Figure 4, we present superimposed graphs of quiet and disturbed day *PoI* as well as daily peak values of foEs. It is important to mention that the daily peak values were those presented in Figure 2. Panels in columns (i), (ii), and (iii) of Figure 4 correspond to DAEJ, KGNI, and TO536 respectively, while rows in panels (a) – (f) correspond to the years 2010 – 2015, respectively. The red and blue dots represent either *PoI* or daily peak value of foEs during disturbed and quiet geomagnetic days, respectively. A quiet day was identified when all the 8 values of Kp within the day were < 3. On the other hand, in order to observe the impact of a fairly strong geomagnetic disturbance, such days were identified when one of the 8 Kp values in the day was >5. The Kp values were obtained from the world data center at Kyoto University, Japan (<http://swdcwww.kugi.kyoto-u.ac.jp/>).

Both quiet and disturbed *PoI* in Figure 4 appear higher during the summer months compared to other months. The high *PoI* during quiet days may be associated with Es and MSTIDs which are frequent during the same period. The low *PoI* on a quiet day (especially in summer month when high value is expected) may be associated with a preceding disturbed day where Kp > 5 occurred in the last 6 hours. Future studies could investigate prevalence of such events. Still in Figure 4, cases exist where disturbed (quiet) geomagnetic *PoI* values are higher than quiet (disturbed) values. This implies that disturbed geomagnetic conditions may either increase or reduce the *PoI* most probably based on the underlying ionospheric conditions or dynamics. As stated before, there are several factors that could affect the occurrence of ionospheric irregularities during disturbed geomagnetic conditions. Pi et al. (1997) presented global ROTI maps corresponding to January 10, 1997 when there was a geomagnetic storm (Dst reached -80 nT). Ionospheric irregularities were observed about after 1 hour following sudden storm commencement. Six hours later, GPS phase fluctuations became stronger and irregularity regions expanded in the post-midnight sectors at northern high latitudes, and in the evening sectors in the Antarctic region.

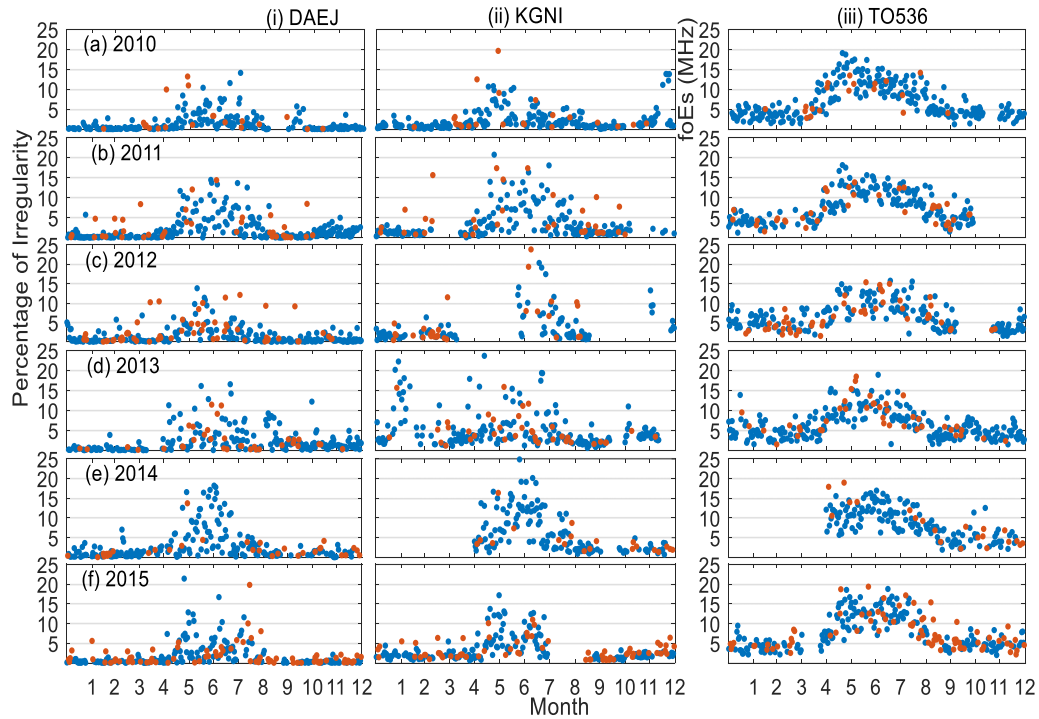


Figure 4: Daily percentages of irregularities over DAEJ (column (i)) and KGNI (column (ii)) and peak values of foEs over TO536 (column (iii)). Panels in rows (a) - (f) present data during the years 2010 - 2015, respectively. The red and blue dots are data during disturbed and quiet geomagnetic days, respectively.

Panels in column (iii) of Figure 4 depict that disturbed geomagnetic conditions do not always result in higher/lower foEs values (see red dots) compared to those on quiet conditions (see blue dots). As mentioned before, some studies report good (e.g., Whitehead, 1970) while others report weak or no correlation (e.g., Rishbeth and Garriott, 1969) between Es and geomagnetic activity.

To inspect the solar flux dependence of irregularities, we compared the percentages of irregularities (red lines) with the average values of the solar flux F10.7 index during the years 2010 – 2015, as presented in Figure 5. Figures 5a and 5b represent the percentage of irregularities over DAEJ and KGNI, respectively. Furthermore, Figure 5c presents the percentage of foEs >5 MHz over TO536. The percentage of either irregularity or foEs >5MHz in a particular year was determined using an expression that takes the form of equation 2. As Figure 2 and later Figure 6 show that majority of the low values of foEs occur below 5 MHz, this value was considered in determining percentage of Es occurrence. The F10.7 indices used in this study were obtained from the web site of the Goddard Space Flight Center (<https://omniweb.gsfc.nasa.gov/form/dx1.html>).

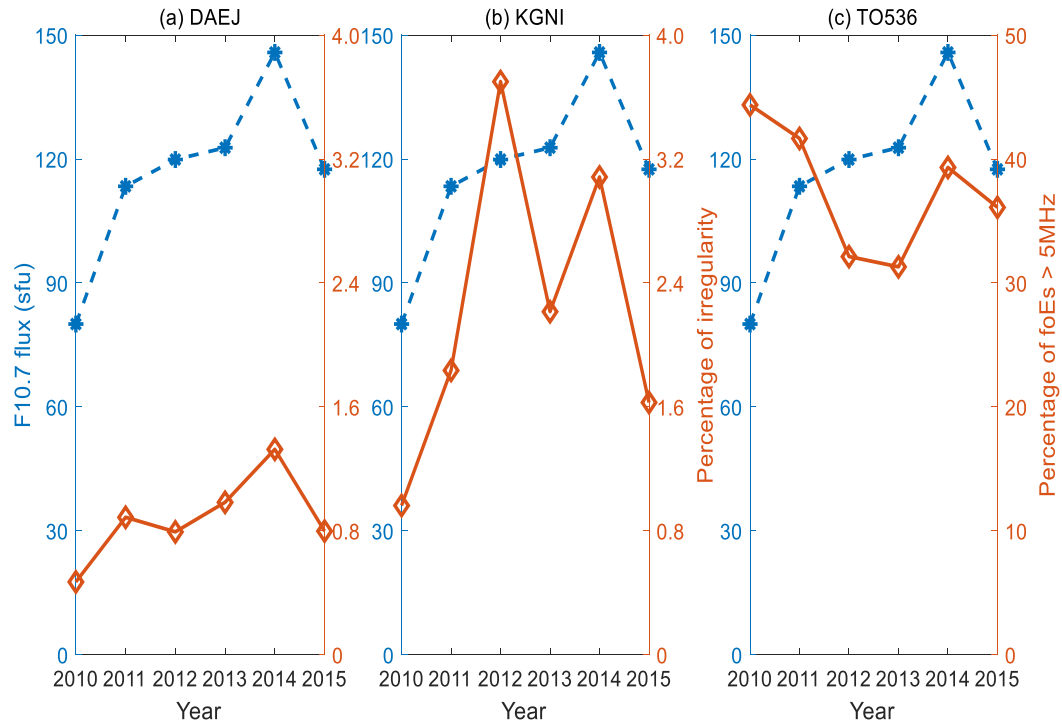


Figure 5: The red lines present percentage of irregularity occurrence over DAEJ (panel (a)) and KGNi (panel (b)) as well as the percentage of foEs >5MHz over TO536 (panel (c)) during the years 2010 -2015. The blue lines present average F10.7 flux during the corresponding years.

Figure 5 depicts a positive correlation between solar flux levels and percentage of irregularities. The correlation coefficient, r over DAEJ and KGNi were determined as 0.95 and 0.72, respectively. Due to the unclear relationship between F10.7 flux and percentage of foEs >5MHz depicted in Figure 5c, it may not be reasonable to relate the observed increase of irregularity occurrence to existence of Es-layer. Based on the data presented in Figure 5c, r associated with solar flux level and percentage of Es occurrence over TO536 was -0.48. In fact, some studies have reported positive correlation between Es occurrence and solar flux level (e.g., Atulkar et al., 2016) while others report no or weak correlation (e.g., Pietrella et al., 2014 and Jo et al., 2019).

Therefore, the increase in the percentage of irregularity occurrence with the F10.7 flux level might be attributed to MSTIDs. Hernández-Pajares et al. (2006) reported that MSTIDs are more frequent near the solar cycle maximum. They argued that TIDs might be produced by interactions between neutral particles and ionized particles. Therefore, the effectiveness of gravity waves in producing TIDs will be greater near the solar cycle maximum when there is considerable ionization. MSTIDs can be identified by the deviations of TEC from a baseline value of GPS measured TEC (e.g., Ding et al., 2011; Chen et al., 2019). In our study, the TEC perturbations due to MSTIDs may manifest as high ROTI values. Although MSTIDs are

commonly identified in the F region (e.g., Ssessanga et al., 2017), the irregularities associated with MSTIDs may reach down the E-region, particularly during night-time. Otsuka et al. (2007) reported irregularities in both F- and E-regions by making simultaneous observations of very high frequency radar backscatter from field-aligned irregularities in the E-region and MSTID in 630-nm airglow images. Saito et al. (2007) deduced that the irregularities in the E- and F-regions (MSTIDs) were closely coupled.

Another point worth noting from Figure 5 is that the percentages of irregularity occurrences are generally low ($< 4\%$). This result is in agreement with previous reports of observing the fewest irregularities and scintillations over mid-latitude regions (Basu et al., 2002). Pi et al. (1997) presented global ROTI maps around the solar flux minimum period, indicating that ROTI values over South Korea and Japan mostly are below 1 TECU/min with values > 3 TECU/min over some other regions. By analyzing phase scintillation observations over Usuda, Japan, Wanninger (1993) concluded that phase scintillations over the station were not as severe as those observed close to the magnetic equator where electro-dynamic processes of ExB drift that drives ionospheric irregularity formation (Kelley, 2009).

Despite the low levels of irregularity occurrences over our study area, it can still be observed that the percentage of irregularity occurrence over KGNI appears to be greater than that over DAEJ. This trend seems to be consistent with the world-wide distribution of Es-layer, with the greatest occurrence over the Far East (Whitehead, 1970). Since the Es is more frequent over KGNI than DAEJ, and the irregularities have been highly associated with Es occurrence, it is reasonable to expect the low percentage of irregularity occurrence over DAEJ compared to KGNI. Figure 6 provides more evidence of Es intensity being greater over Japan than South Korea. Panels (a) and (b) represent foEs over IC437, South Korea, and Kokubunji (TO536), Japan, respectively, during the year 2011. Evident in summer months is high occurrence of foEs (> 10 MHz) over TO536 compared to that over IC437 (on average < 5 MHz).

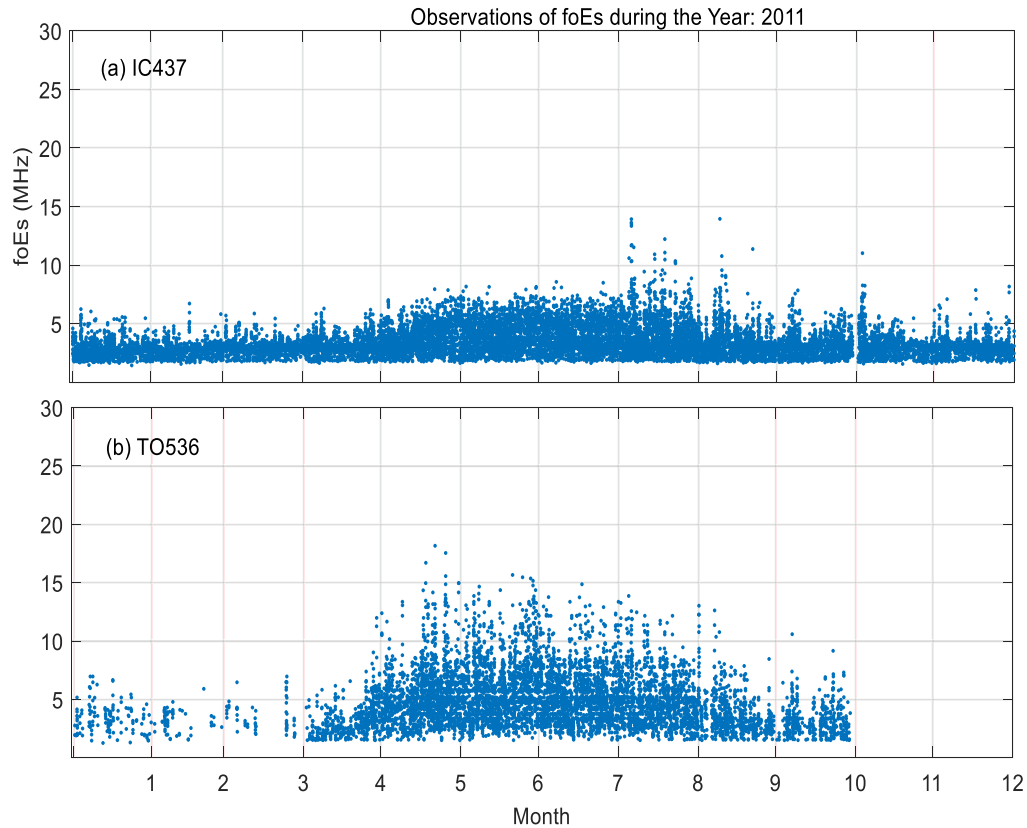


Figure 6: Observations of foEs over (a)Icheon (IC437), Korea and (b)Kokubunji (TO536), Japan during the year 2011.

More comprehensive studies are needed to explain the observed differences in the strengths of foEs over South Korea and Japan. However, the direction of zonal winds (e.g., Larsen et al., 1998) and frequency of occurrence of gravity waves at a particular location (e.g., Wang et al. 2019) might be potential candidates responsible for the spatial variations of foEs. Since ionospheric irregularities are also detected as MSTIDs and yet MSTIDs are associated with gravity waves, the exceptionally high percentage of irregularity in the year 2012 over KGNI (see Figure 5b) might imply that in this year, gravity waves were more frequent than other years. To justify this claim, the study by Choo et al. (2018) which mentioned that multiple tornados occurred over Japan on 6th May 2012 needs to be extended to present statistics of occurrences of gravity waves during the years 2010 – 2015.

3.3. Local time dependence of ionospheric irregularity occurrence

In order to establish the dependence of ionospheric irregularities on local time (LT), the ROTI data of the entire study period were first sorted according to the four seasons, namely; summer (June, July, and August), autumn (September, October, and November), spring (March, April, and May), and winter (December, January, and February). The data were then sorted according to LT. Finally, the number of ionospheric irregularities (ROTI values that exceed the background) within hourly intervals were established. The results over KGNI

(panels in row (a)) are presented in Figure 7. Since some of the ionospheric irregularities were suspected to be associated with Es occurrence, row (b) was added corresponding to variation of average foEs over TO536 as a function of LT. The average foEs values were determined using the data of the entire study period. Panels in columns (i) – (iv) correspond to summer, autumn, winter, and spring, respectively.

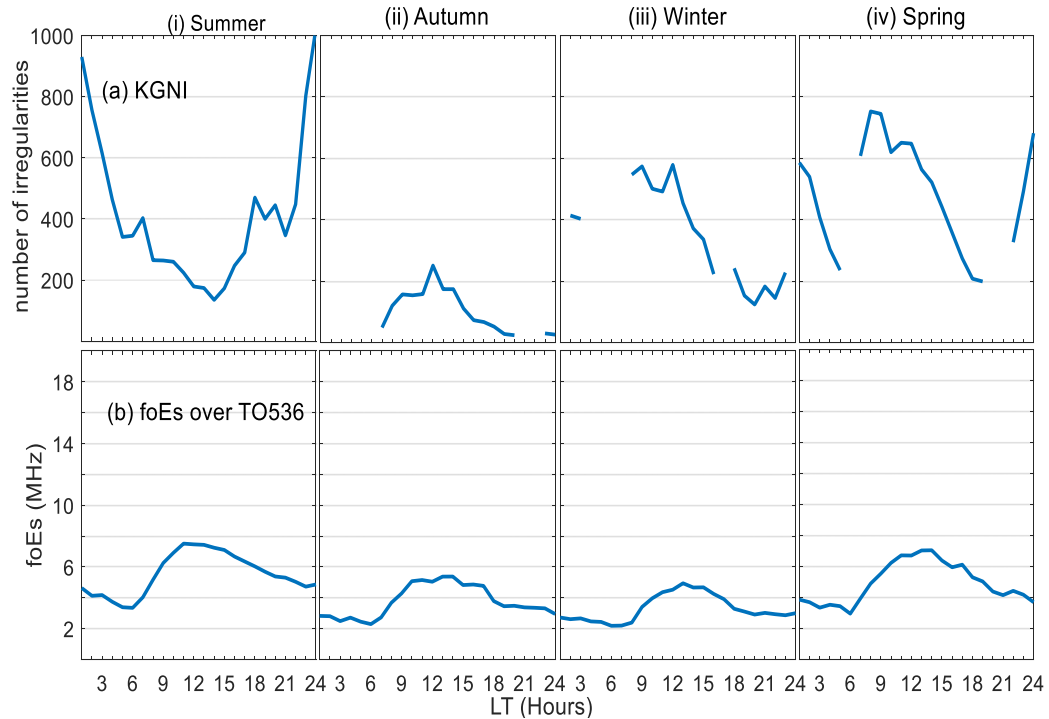


Figure 7: Panels in row (a) present the number of observed ionospheric irregularities over KGNU, while panels in row (b) present the average foEs over TO536. Panels in columns (i) – (iv) present the variations of number of irregularities and average foEs as a function of LT during summer, autumn, winter, and spring, respectively.

Panels in row (a) of Figure 7 clearly show peaks in number of irregularities over KGNU during day-time in most seasons, except summer which depicts a small peak just before 09:00 LT and at around 18:00 LT. The considerable day-time irregularity occurrence in summer may be appreciated by noticing that the irregularities during day-time in summer are comparable or greater than the distinct peaks during the day-time of other seasons. These day-time irregularities might be associated with Es-layer. This is corroborated by the increased day-time Es occurrence depicted in panels in row (b) of Figure 7. Day-time Es occurrence over mid-latitudes has also been previously reported by Atulkar et al. (2016) and Jo et al. (2019). Therefore, because this daytime trend is also observed in ROTI data, as previously discussed, ionospheric irregularities with scale sizes in the range of 0.4 – 2.5 km might exist within the Es-layer structures. It is also probable that the observed day-time irregularities in

Figure 7 (a) are partly due to MSTIDs which occur during daytime in winter (e.g., Wanninger, 1993; Chen et al., 2019; and Ding et al., 2011).

Still in Figure 7, panels of row (a) show a large number of irregularities at night, particularly in the seasons of summer and spring. Wanninger (1993) reported that over Usuda Japan, small scale ionospheric irregularities mainly occur at night during summer months. As already discussed in section 3.1, the high occurrence of irregularities at night might be associated with MSTIDs (Hernández-Pajares et al., 2006). In conclusion the local time trend of irregularity occurrence closely links the irregularities to Es-layer.

3.4. ROTI critical values

For the purpose of interpreting regional ROTI maps as an ionospheric monitoring system, it is important to know the background ROTI value, median, and extreme ROTI values due to ionospheric irregularities. The ROTI data whose values were less than BGR (determined as in subsection 3.1) were discarded and the remaining data were used to determine the median and extreme ROTI values associated with ionospheric irregularities. First, the ROTI data were sorted according to year since Figure 5 showed that ionospheric irregularity percentage increases with the solar activity proxy (F10.7). As the irregularities appear to maximize at night (20:00 – 24:00, 0:00 – 03:00 LT) and around midday (10:00 – 15:00 LT), the median and 95th percentile of ROTI values during these two-time intervals were determined. To avoid considering the maximum value which may be an outlier as the extreme ROTI measurement, the 95th percentile of the ROTI values was computed and presented in Figure 8. Panels of rows (a) and (b) are for the median and 95th percentile of the ROTI values, respectively, and columns (i) and (ii) are for DAEJ and KGNI, respectively. The blue and red bars represent the ROTI values during day and night, respectively. Noticeable, in panels of row (a) for each station, the median ROTI's appear not to differ significantly both during night and day. In fact, the overall median of ROTI values (both day and night) over DAEJ and KGNI were determined as 0.131 and 0.125 TECU/min, respectively. Panels in row (b) of Figure 8 depict that the extreme cases (95th percentile) of ROTI values over a station at night are in most cases greater than those during the daytime. Therefore, the extreme cases of ROTI values over a station during day and night were separately averaged. Over DAEJ, the ROTI values may exceed 0.246 and 0.314 TECU/min during day and night, respectively. On the other hand, over KGNI, the ROTI values may exceed 0.217 and 0.339 TECU/min during day and at night, respectively. Generally, the mid-latitude ROTI values are weaker compared to low latitude ROTI values reported in the literature. For example, Pi et al. (1997), Tanna et al. (2013), and Mungufeni et al. (2015) obtained ROTI values >0.5 TECU/min that were associated with low latitude ionospheric irregularities.

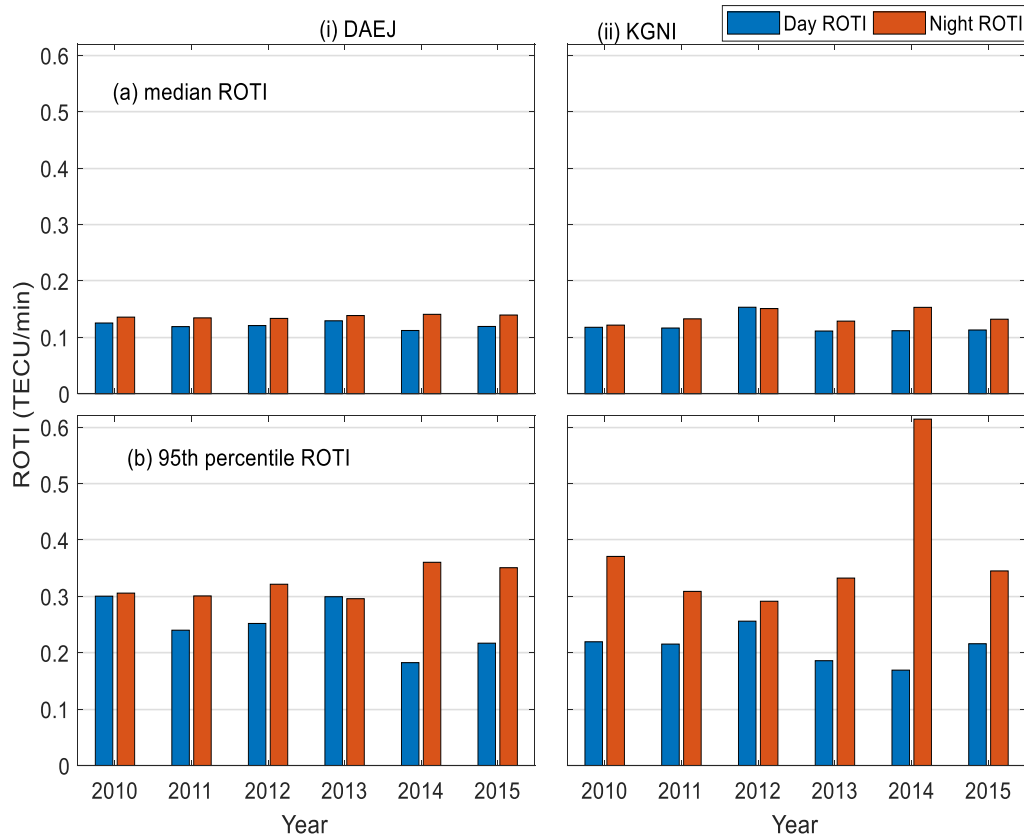


Figure 8: Critical ROTI values over (a) DAEJ and (b) KGNI. Blue and red bars present 95 percentile of ROTI values during day and night, respectively.

4. Conclusions

We have analyzed the occurrence of ionospheric irregularities over South Korea and Japan. The ROTI values >0.1 TECU/min (given by equation 1) were associated with occurrence of ionospheric irregularities that have scale sizes in the range of 0.4 – 2.5 km, as suggested in previous studies. The results indicate that ionospheric irregularities mostly occur at night-time and around local noon-time. The occurrence of the irregularities appears to maximize in the seasons of summer and late spring. Furthermore, the percentage of irregularities increases with the solar activity proxy, F10.7. The ionospheric irregularities defined by ROTI seem to be associated with Es. The percentage of the irregularity occurrence over Japan exceeds that of South Korea. This was found to be consistent with the intensity of Es observed by ionosondes over Japan and South Korea.

The median ROTI associated with ionospheric irregularities over DAEJ and KGNI were 0.131 and 0.125 TECU/min, respectively. For the top 5 percentage, the ROTI values over DAEJ (KGNI) can exceed 0.246 (0.217) and 0.314 (0.339) TECU/min during day and night, respectively. These critical ROTI values could be vital to the ionospheric

irregularity monitoring systems, not only over South Korea and Japan but the mid-latitudes as a whole.

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II. Modeling Total Electron Content derived from radio occultation measurements by COSMIC satellites over the African region

1. Introduction

Among the error sources that affect the positioning in Global Navigation Satellite Systems (GNSS) are the propagation medium related errors. In particular, the ionospheric refraction is the largest contributor of the user equivalent range error. This type of frequency dependent error can virtually be eliminated in dual frequency receivers by differential techniques (Hofmann-Wellenhof et al., 2007). For the case of single frequency receivers, some GNSS (e.g Global Positioning System (GPS) and Galileo) broadcast message includes the parameters of an ionospheric model which can be used to compute and correct the ionospheric effects (Guochang, 2007). For instance, the GPS uses the Klobuchar model which represents the zenith delay as a constant value at night and a half cosine function during the day (Klobuchar, 1987). In the framework of the European Galileo constellation, the NeQuick G based on NeQuick model has been proposed to be used for single frequency positioning (see Issue 1.2, September, 2016 of European Commission, titled, European GNSS (Galileo) Open Service - Ionospheric correction algorithm for Galileo single frequency users). The NeQuick and its subsequent modifications (NeQuick G and NeQuick 2) are a three-dimensional, time dependent ionospheric electron density model developed by the Aeronomy and Radio Propagation Laboratory (ARPL) of the Abdus Salam

International Center for Theoretical Physics (ICTP) in Trieste, Italy and the Institute for Geophysics, Astrophysics and Meteorology of the University of Graz, Austria (Nava et al., 2008). In addition to using models to reduce ionospheric refraction errors, Space Based Augmentation Systems (SBAS) such as the Wide Area Augmentation System (WAAS), the European Geostationary Navigation Overlay Service (EGNOS), and the GPS-aided Geo Augmented Navigation (GAGAN) are also used (Hofmann-Wellenhof et al., 2007).

For the international standard specification of ionospheric parameters (such as electron density, electron and ion temperatures, and equatorial vertical ion drift), the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI) recommended the International Reference Ionosphere Model (IRI) (Bilitza, 2001). IRI is an empirical model primarily based on all available experimental data (ground and space based) sources. However, theoretical considerations have been used in bridging data gaps and for internal consistency checks (Bilitza, 2001).

The ionospheric Total Electron Content (TEC) is one of the important descriptive physical quantities of the ionosphere (Rama Rao et al., 1997; Ercha et al., 2012). The GNSS measurements obtained from the global and regional networks of

International GNSS Service (IGS) ground receivers have become a major source of TEC data. As one of the IGS analysis centers, Center for Orbit Determination in Europe (CODE) provides Global Ionosphere Maps (GIMs) containing vertical TEC data daily using the GNSS data collected from over 200 tracking stations of IGS and other institutions. Several studies have used GIMs from CODE and other IGS analysis centers such as the Jet Propulsion Laboratory (JPL) to construct TEC models (Jakowski et al. 2011a; Mukhtarov et al. 2013; Ercha et al. 2012; Sun et al., 2017). Jakowski et al. (2011a) proposed the Global Neustrelitz TEC Model (NTCM-GL) that describes the average TEC under quiet geomagnetic conditions. The NTCM-GL was developed using GIMs during 1998 - 2007 provided by CODE. A global background TEC model was also built using CODE GIMs by Mukhtarov et al. (2013). The model describes the climatological behavior of the ionosphere. The GIMs from JPL were used by Ercha et al. (2012) to construct a global ionosphere model using Empirical Orthogonal Function (EOF) analysis method. The Taiwan Ionosphere Group for Education and Research constructed a global ionosphere model from GNSS and the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) GPS radio occultation (RO) observations (Sun et al., 2017). The map of all the averaged Root Mean Squared (RMS) error values of CODE GIMs during the years 2010 - 2012 presented by Najman and Kos (2014) showed high values over low latitude African regions. This could be due to the poor distribution of IGS tracking stations over Africa and inability of the spherical harmonics function used in GIM to describe ionospheric structure over low latitudes.

In addition to the existing GIMs discussed in the previous paragraph, regional TEC maps and models have also been constructed. In comparison with the global models, regional TEC models might have better accuracy over the particular region for which it was constructed. Opperman (2008) stated that the higher time and spatial resolution imaging achievable with regional models permits the analysis of localized ionospheric structures and dynamics not observable in global models. Examples of studies that developed TEC models over some parts of Africa are the following. A neural network model of GNSS - vertical TEC (GNSS-VTEC) over Nigeria was developed by Okoh et al., (2016) using all available GNSS data from the Nigerian GNSS Permanent Network (NIGNET). An adjusted spherical harmonic-based TEC model was developed by Opperman, (2008) using a network of South African dual frequency GPS receivers. Habarulema et al., (2011) presented the Southern Africa TEC prediction (SATECP) model that was based on the Neural Network technique. The SATECP generates TEC predictions as function of input parameters, namely, local time, day number of the year, solar and magnetic activity levels, and the geographical location. A neural network based ionospheric model was developed using GPS-TEC data over the East African sector by Tebabal et al. (2019). Recently, Okoh et al., (2019) used neural network technique to develop TEC model over the entire African region. In addition to using TEC obtained by COSMIC RO technique, they used TEC measured by GPS receivers on ground. Due to the lack of a dense network of ground-based GNSS receivers and poor coverage of

COSMIC RO data over the African region, the TEC model over the entire African region presented by Okoh et al. (2019) sometimes failed to capture the equatorial ionization anomaly (EIA) over the region. This point has been illustrated with examples in sections 2 and 5. In this study, we applied data binning method to the COSMIC RO TEC data that allowed development of an improved TEC model over the region. Moreover, we demonstrate the potential of the basis spline functions to model TEC over the African region. These basis functions never vanish over limited intervals and add up to one at all local times and longitudes (De-Boor, 1978). Moreover, according to Scherliess and Fejer, (1999), they are ideally suited to model the equatorial ionosphere which exhibit smooth and rapid changes during daytime and near sunset, respectively, by proper placement of the mesh of nodes.

2. The Data and methods

2.1 Data sources

In order to overcome the problem of lack of a dense network of ground based GNSS receivers over the African region, this study used TEC data obtained from RO measurements done by the COSMIC satellites. The integrated electron density (integration being done up to the altitudes of the COSMIC satellites) which is being referred to as TEC in this study can be obtained from ionPrf files which are processed at the COSMIC Data Analysis and Archive Centre (CDAAC)(<http://cosmic-io.cosmic.ucar.edu/cdaac/index.html>). The TEC for the individual occultation events were assigned to the geographic coordinates of NmF2 in the same file.

In order to get integrated electron density approximately up to the altitudes of GPS satellites, Okoh et al., (2019) used neural networks to learn the relationship between coincident TEC measurements done by ground based GPS receivers and COSMIC RO. They showed that the ratio between TEC data from the two sources vary spatially. This observation implies that the neural networks may not learn very well the relationship between TEC measured by ground-based GPS receivers and COSMIC RO over locations which do not have the former data set during the entire study period. As it can be seen in Figure 1 of Okoh et al., (2019), there were large spatial coverage's that do not have ground-based GPS receivers. Unlike what has been done in Okoh et al., 2019 and Mungufeni et al., 2019, in the current work we used only COSMIC TEC without any adjustments.

In this regard, an analysis of coincident ground-based GNSS TEC and TEC from COSMIC occultation data performed by Mungufeni et al. (2019) reveals that the upper quartile of the differences between the two data sets may reach up to ~11 TECU over the northern crest of the Equatorial Ionization Anomaly. Over the southern mid-latitude region, the differences were low (~4 TECU). Since the upper quartiles of the differences can reach up to ~11 TECU, the median/mean values in the worst cases might obviously be much lower than this value. This might be the reason for observing most of the well-known ionospheric TEC features

over the African region when the COSMIC RO TEC were appropriately binned as in Mungufeni et al. (2019). Therefore, this study used the TEC obtained from COSMIC occultation measurements to develop TEC model over the African region in order to reproduce these ionospheric features. Such endeavors are important for educational purposes.

During geomagnetic storms, the variations in zonal electric fields and composition of the neutral atmosphere contribute significantly to the occurrence of negative and positive ionospheric storm effects in the low latitude region (Rishbeth and Garriot, 1969; Buonsanto, 1999; Adewale et al., 2011). Therefore, since the ionosphere changes in a complex manner during geomagnetic storms, we only considered data on quiet days. The quiet geomagnetic days were identified by examining the 3 hourly Kp and Disturbance storm time (Dst) indices that were obtained from the World Data Center of Kyoto, Japan (<http://swdcwww.kugi.kyoto-u.ac.jp/>). A day was considered to be quiet if all the 8 Kp values in that day were ≤ 3 . In addition to satisfying this condition, the hourly values of Dst in that day should also have values ≥ -20 nT. The two conditions were applied to ensure that both low and mid/sub-auroral latitude geomagnetic disturbances are detected by Dst and Kp indices, respectively. In future, we intend to use TEC data during disturbed geomagnetic conditions to construct a TEC model during geomagnetically disturbed conditions.

2.2 Methods of Data Analysis

The TEC data during the years 2008 - 2011 and 2013 - 2017 were used for developing the TEC model over the African region. Due to the adequate data needed to develop an empirical model, we only reserved the data of the years 2012 and 2018 for validation. The period considered in this study represents data of both low and high solar activity level in sunspot cycles 23 and 24. The data within geographic latitude and longitude ranges of -35° – 35° and -20° – 60° , respectively, were used to cover the African region. Table 1 presents the number of days per year when there were TEC data over the African region. Since there are many geomagnetically disturbed days in high (2012 - 2015) and medium (2011 and 2016) solar activity years, the number of days with data is also reduced in such years compared to low solar activity years (2008 - 2010, 2018).

Table 1: Distribution of number of days with data

Year	Number of Days with data
2008	219
2009	293
2010	235
2011	174
2012	169
2013	185

2014	164
2015	128
2016	151
2017	154
2018	211

It would be good to bin the TEC data according to geomagnetic latitudes since many structural and dynamical features of the ionized and neutral upper atmosphere are strongly organized by the geomagnetic field (e.g. Emmert et al., 2010). This may be complicated since geomagnetic latitude lines are not usually straight. For convenience and simplicity, we binned the data based on geographic coordinates. In order to observe small scale ionospheric structures, small grid resolutions of 3 and 5 degrees in geographic latitude and longitude, respectively were used to bin the TEC data. These grid resolutions resulted into 24 and 16 latitudinal and longitudinal bins, respectively. Several studies (e.g. Krankowski et al., 2011 and Mengist et al., 2019) that have used COSMIC data commonly consider measurements with horizontal smear > 1500 km prone to errors and they reject such measurements. We established that after applying this restriction, there were ~40 RO measurements per day during the year 2013 over our study area (not shown here). Based on the previous discussions, this value is far less than the 9,216 (16 longitudinal, 24 latitudinal, and 24 local time) TEC data points required in all grid cells in a day. As stated in section 1, this poor amount of data to represent day of year TEC variation might be the reason for the failure of TEC model presented by Okoh et al. (2019) to capture in some cases the EIA over the African region. Another reason might be the discrepancy which arises due to some locations being represented by adjusted COSMIC RO TEC while others by the ground-based GPS TEC data.

Since empirical modeling requires adequate data for the mathematical functions to capture the physics inherent in the data, this study did not reject COSMIC RO TEC measurements with horizontal smear > 1500 km. Although not presented here, we observed that the COSMIC TEC data values with smear > 1500 km did not introduce alarming errors. This observation was made when we analyzed COSMIC TEC data which were coincident with TEC observed by ionosonde stations over South Africa (see details in section 5.2) located at Hermanus, Grahamstown, and Louisvale. Interestingly, compared to measurements with horizontal smear > 1500 km, some measurements with horizontal smear < 1500 km were observed to be far from the linear least squares fitting line. Further analysis of COSMIC RO observations over our study area revealed that without restricting horizontal smear, there were ~80 RO measurements per day during the year 2013 (not shown here). Still this value is far less than the 9,216 TEC data values required to fill all spatial grid cells in a day. To partially solve this problem, instead of binning data according to year, we binned the data according to different solar flux levels as shown below.

For each spatial grid cell, the data were binned at 1-hour interval. TEC values within the bins were averaged to yield 1-hour resolution TEC data over the grids. TEC data for the different days were binned according to F10.7 flux of that day. The F10.7 flux indices were obtained from the Space Weather Prediction Center (SWPC) of the National Oceanic and Space Administration (NOAA) (<http://www.swpc.noaa.gov/>). The F10.7 flux ranges for low solar activity (LSA), medium solar activity (MSA), and high solar activity (HSA) were < 76, 76 - 108, and > 108 sfu, respectively. The boundary values 76 and 108 sfu of the F10.7 flux ranges correspond to the 75th and 25th percentiles of all F10.7 flux values on the days in low (2008 - 2010, 2017 -2018) and high (2012 - 2015) solar activity years, respectively.

Table 2: Average monthly F10.7 flux values used in the study

Month	F10.7 flux (sfu)		
	LSA	MSA	HSA
January	71.10	83.94	140.65
February	71.14	87.06	126.23
March	69.81	85.40	130.98
April	71.02	86.09	130.46
May	70.29	90.59	123.80
June	69.51	89.91	118.73
July	68.09	88.14	128.92
August	67.45	85.46	114.53
September	69.20	86.34	122.98
October	70.06	81.88	131.50
November	71.66	82.40	142.95
December	70.82	82.97	142.72

The data within a specific solar flux bin were further binned based on months of a year. The average of the corresponding F10.7 flux of the days used to represent seasonal TEC were determined and used to capture the variation of TEC with solar flux. Table 2 presents the average F10.7 flux values that were determined in the months of a year. In summary, a total of 331,776 TEC data values were needed to exist in 16 longitudinal, 24 latitudinal, 3 solar flux, 12 monthly, and 24 hourly bins, in order to determine the model coefficients. However, from the data of the entire study period, only 121,447 bins were filled with TEC data values. The average of the standard deviations of the bins that contained more than 1 TEC data during low (sample size = 21,108), medium (sample size = 6,180) and high (sample size = 7,495) solar flux levels were 1.28, 2.15, and 4.31 TECU, respectively.

The bins which did not have TEC data were filled by estimation following the procedures described in 3 steps below.

1. At a particular spatial grid cell, the diurnal TEC was divided into two local time sectors, namely, (i) 10:00 – 24:00 LT, and (ii) 0:00 – 10:00 LT. Sector (i) which is day

time and before mid-night includes the time when daily and secondary TEC peaks are expected, while (ii) which is mostly at night is when TEC varies slowly. When slow variation of TEC was expected as in sector (ii) and there were at least a few (> 2) TEC data available, smoothing spline (De-Boor, 1978) data fitting method was used to estimate missing TEC values. In cases where rapid TEC variations are expected as in sector (i) and at least half of the total expected number of data points were filled with TEC data, piece-wise cubic interpolation (De-Boor, 1978) data fitting method was used to estimate missing TEC values. For example, when there were at least 4 measurements in sector (ii) the missing values were obtained by evaluating the fitted function through the existing TEC data values. On the other hand, when there were at least 7 (half the number of hours during 10:00 – 24 LT) TEC values in sector (i), the missing values were obtained by evaluating the fitted function to the available data values. After estimating the missing TEC data from the two sections of the diurnal TEC, the entire diurnal TEC data over a particular grid cell was then considered to estimate the missing values. When there were at least 12 (half the number of hours in a day) values, the missing values were obtained by evaluating a smoothing spline function fitted to the existing data values.

2. At a particular latitude and local time, the values of TEC along all the longitudes were divided into western ($-20 - 20^\circ \text{E}$) and eastern ($20 - 60^\circ \text{E}$) longitude sectors. Each of the longitude sectors contained 8 bins. At night, when there were at least 3 TEC values over any longitude sector, the missing values were obtained by evaluating smoothing spline function fitted to the available data points, while during the day, when there were at least 4 Tec values, the missing values were obtained by evaluating a smoothing spline function fitted to the available data points. After estimating the missing TEC values over the two longitude sectors, the TEC over all longitudes were then considered to estimate the missing values. At night, when there were at least 8 values, the remaining values where obtained by evaluating a smoothing spline fitted to the available TEC data points. The missing values during day-time were estimated when there were at least 10 measurements available.
3. Procedure 3 is similar to 2, except for variations of TEC as a function of latitude were considered at specific values of longitude and time. TEC values over the latitudes were divided into lower ($-35 - 0^\circ \text{S}$) and upper ($0 - 35^\circ \text{N}$) latitudinal sectors. There were 12 bins in each of the latitudinal sector. To estimate missing TEC values at night over a latitudinal sector, at least 4 measurements were required to be available, while during the day, at least 6 values were required. When TEC data over the combined latitudinal sectors were considered to estimate the missing values, at least 12 values were required to be available.

After repeating procedures 1 – 3 three times, all the 331,776 bins were filled with TEC data. For purposes of minimizing the effects of outliers, the diurnal TEC at spatial grid cells were then separately fitted with smoothing splines which were evaluated to obtain the TEC data that were later used to determine the model coefficients as explained in section 3. In order to demonstrate the appropriateness of our estimation of missing TEC data values and its use for determining model coefficients, we present Figure 1. Panels (a) – (c) of the figure present the available TEC data (*) and estimated (red line) TEC values during low, medium, and high solar flux levels, respectively.

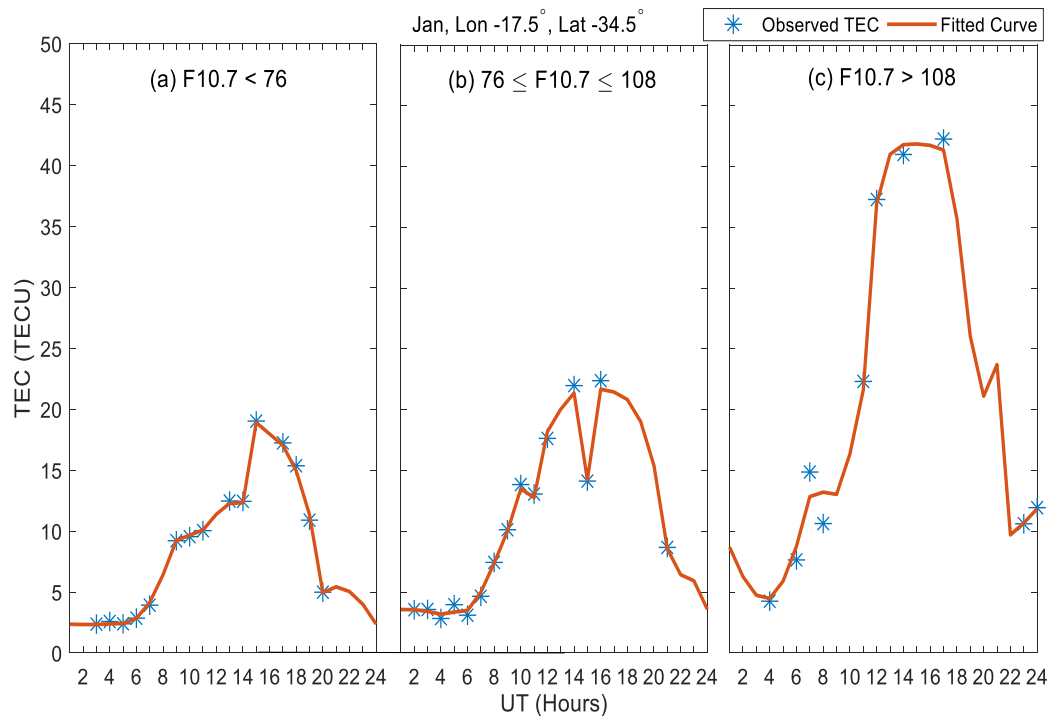


Figure 1: Panels (a) – (c) present available (*) and estimated (red line) TEC values during low, medium and high solar flux levels, respectively. The data are for the month of January and fall within the grid cell centered at longitude and latitude of 17.5° W and 34.5° S, respectively.

The TEC data plotted in Figure 1 correspond to January and the grid cell centered at longitude 17.5° W and latitude 34.5° S. Figure 1 clearly shows that the available and estimated TEC variations depict the well-known diurnal and solar activity level dependence patterns. Moreover, the figure shows that the available data values are in most cases close to the estimated TEC values. Therefore, the estimated TEC values were then used to obtain the model coefficients.

3. The Model

The TEC over the African region was expressed as

$$TEC(t, d, F, \lambda, \phi) = \sum_{i=1}^{24} \sum_{j=1}^{12} \sum_{k=1}^3 \sum_{l=1}^{16} \sum_{m=1}^{24} a_{ijklm} \times N_i(t) \times N_j(d) \times N_k(F) \times N_l(\lambda) \times N_m(\phi) \quad (1)$$

where the linear model coefficients a_{ijklm} were determined by the least square fitting procedure to the 331,776 TEC data values as in Abdu et al. (2003); Jakowski et al. (2011b); Mungufeni et al. (2015). In Equation 1, $N_i(t)$, $N_j(d)$, $N_k(F)$, $N_l(\lambda)$, and $N_m(\phi)$ are

B splines of different orders to represent variations of TEC with local time, seasons, solar flux level, longitude, and latitude respectively. Most of the B splines were of order 2, except for those used to represent LT and latitudinal variations which were of order 4. The order of splines used to represent LT and latitude was higher to cater for the rapid variations of TEC with these two parameters. Twenty-four local time nodes 1, 2, ..., 24 were used. For simple interpolation between months, seasonal/monthly nodes were placed at the 15th day of each month. Solar flux nodes used in the various months are as shown in Table 2. The longitudinal nodes were separated by 5° and placed at longitudes -17.5, 12.5, 7.5, ..., 57.5 degrees, while the latitudinal nodes were separated by 3° and placed at latitudes -34.5, -31.5, -28.5, ..., 34.5 degrees.

4. Comparison of Observed and Modeled TEC

In order to assess the ability of the model to describe the data used to construct it, modelled data were compared with the binned data that were used to solve equation 1. The results of the self-consistency check are presented in Figure 2. It is important to note that validation using data that was not included during modeling is provided in section 5. Panels in column (i) of Figure 2 present the observed binned TEC data while column (ii) presents the corresponding modeled TEC data. In column (iii), we present the differences between the observed and modeled TEC data, referred to as errors. In Figure 2, rows (a), (b), and (c) correspond to LSA, MSA, and HSA, respectively. The horizontal magenta lines in Figure 2 and later also in Figure 3 indicate the location of ~0° dip latitude on the corresponding panel. As expected, Figure 2 clearly shows that the corresponding modeled TEC almost perfectly matches the observed binned TEC. This can be confirmed by the small (< 0.1 TECU) error values presented in panels of column (iii). The variations of the ionosphere with local time, solar flux level as well as location that are exhibited in Figure 2 gives the confidence of relying on the binned data as a good representation of the ionosphere. The physical explanations for these variations are as follows. The increase of both observed and modeled TEC that occurs when solar flux level increases is usually attributed to increased ionizing radiations in X-ray and Extreme Ultra-Violet (EUV) bands, which in turn leads to increased TEC in the ionosphere (Hargreaves, 1992).

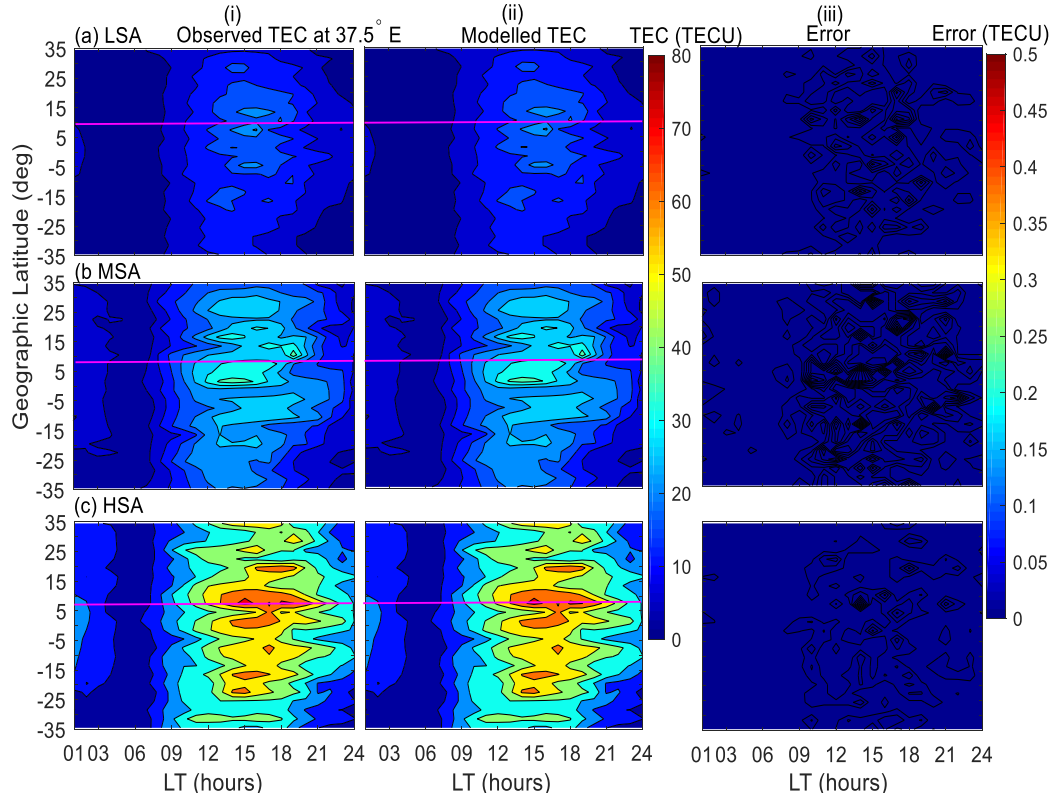


Figure 2. Variation of TEC as a function of geographic latitude and local time in March equinox at 37.5° E. Panels in rows (a) - (c) correspond to LSA, MSA, and HSA, respectively, while panels in columns (i) - (iii) correspond to observed binned, modeled TEC, and difference between observed and modeled TEC (errors), respectively. Magenta line indicates ~0° dip latitude.

The diurnal variation of TEC matches very well with the variation of photo-ionising radiations. At sunrise, the electron density begins to increase rapidly owing to photo-ionization (Schunk and Nagy, 2009). After this initial increase at sunrise, electron density displays a slow rise throughout the day, and then it decays at sunset as the photo-ionization source disappears. Another diurnal feature of variation of TEC exhibited in Figure 2 is the existence of a secondary maximum of TEC. This can clearly be seen in panels of row (c) along the magenta lines, where the first peak occurs at ~15:00 LT and the second at ~18:00 LT. The formation of a secondary maximum of TEC that was mentioned previously may be explained as follows. During the day, the thermospheric wind generates a dynamo electric field in the lower ionosphere that is eastward (Schunk and Nagy, 2009). The eastward electric field, E in combination with the northward geomagnetic field, B produces an upward $E \times B$ drift of the F region plasma. As the ionosphere co-rotates with the Earth toward dusk, the zonal (eastward) component of the neutral wind increases. The increased eastward wind component, in combination with the sharp day-night conductivity gradient across the

terminator leads to the pre-reversal enhancement in the eastward electric field (Batista et al., 1986; Schunk and Nagy, 2009). The F layer therefore rises as the ionosphere co-rotates into darkness. Although in the absence of sunlight after sunset, the lower ionosphere rapidly decays, there exists high electron density at high altitudes, yielding the secondary maximum in TEC.

Panels in rows (b) and (c) of Figure 2 demonstrate the existence of the EIA region, where there exist two belts of high electron density on both sides of 0° dip latitude. The EIA is usually attributed to the upward $E \times B$ drift which lifts plasma to higher altitudes. The plasma then diffuses north and south along magnetic field lines. Due to gravity and pressure gradient forces, there is also a downward diffusion of plasma. The net effect is the formation of the EIA region (Appleton, 1946). Another feature of EIA that can be seen on panels in rows (b) and (c) of Figure 2 is the asymmetry of the crests. Along 120° longitude sector Zhang et al. (2009) reported the asymmetry of EIA crests. As described later at the end of this section, the direction of neutral meridional winds in March may favour high values of electron density over the southern crest.

Generally, Figure 2 shows that, the locations outside the EIA region have lower TEC values compared to locations around and within the EIA region. The low values of TEC over locations outside the EIA region might be due to lower elevation angle of solar radiation flux which is responsible for creation of electrons (Schunk and Nagy, 2009). The solar radiation flux is usually low for locations far from the sub-solar point. The latter situation is dominant over locations outside the EIA region, especially in March. The closeness of the sub-solar point to the locations within the EIA regions result into high solar radiations over these locations. As a result, high TEC values were observed over locations within the EIA region.

To demonstrate that the modeled TEC captures TEC variation with seasons, we present Figure 3. In the figure, columns (i) and (ii) present observed binned and the corresponding modeled TEC respectively. Moreover, rows (a) - (d) present TEC data during March, June, September and December, respectively.

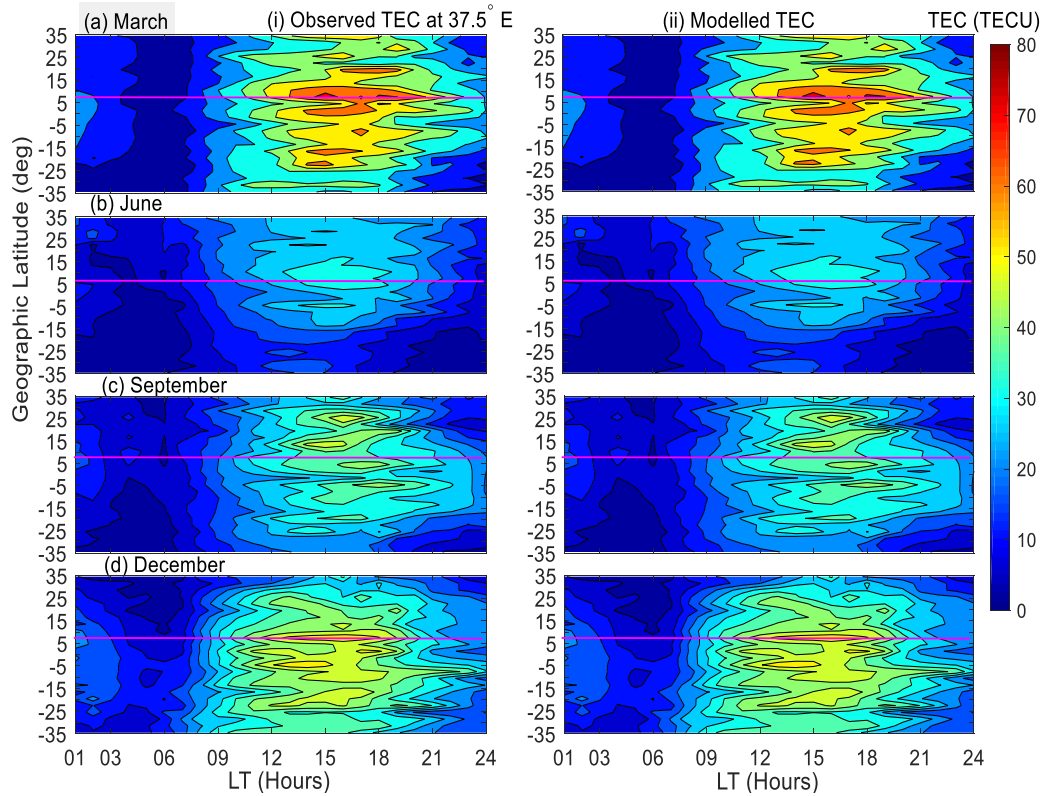


Figure 3. Variation of TEC as a function of latitude and local time in HSA at 37.5°E. Panels in rows (a) - (d) are for March equinox, June solstice, September equinox, and December solstice respectively, while panels in columns (i) and (ii) are observed binned and modeled TEC respectively. Magenta line indicates 0° dip latitude.

As already observed in Figure 2, it can clearly be seen from Figure 3 that the modeled TEC almost perfectly matches the observed TEC data. Among the many features of TEC exhibited by both observed and modeled TEC data, we would like to emphasize the (i) equinoxial asymmetry of TEC, (ii) occurrence of lowest TEC in June solstice, and (iii) high values of TEC in December. Features (ii) and (iii) were recently reported based on a similar data by Mungufeni et al. (2019). The reader may refer to this study for more discussions. Mungufeni et al. (2016a) observed equinoxial asymmetry when studying ionospheric irregularities over the African low latitude region. They observed over the East African region that, the irregularity strength in March equinox was higher than that in September equinox. They attributed the equinoxial asymmetry to meridional winds in March which might blow northward. Such a direction would lift plasma up where recombination is not common. On the other hand, in September, the winds might blow southward. This could lead to recombination at low altitudes.

5. Model Validation

5.1 Validation using reserved COSMIC RO TEC

In addition to comparing observed binned TEC with the corresponding modeled TEC, we validated our model using observed TEC in the years 2012 and 2018. The data during these two years were not used in developing the model. The TEC data in the years 2012 and 2018 were binned according to local time and spatially in a similar manner to that mentioned in subsection 2.2. The corresponding local time, day of the year, solar flux, and spatial coordinates of the data were noted and then used to generate the corresponding modeled TEC. Despite the advantages of B spline modeling mentioned in section 1, one of its limitations is the inability to extrapolate. Therefore, in situations where the solar flux level is higher (lower) than those specified in Table 2, the maximum (minimum) value in the table was used to generate the corresponding modeled TEC. This idea was also applied when the day number of year, longitude, and latitude values were higher (lower) than those specified in section 3.

Figure 4 presents a scatter plot showing the observed TEC against the corresponding modeled TEC. The red line in the figure indicates linear least squares fit to the data in the panel. Furthermore, indicated in Figure 4 are: (i) the correlation coefficients, r , (ii) the r squared values, (iii) the number of data points, n plotted and (iv) the root mean squared error, RMSE when the modeled TEC is used to represent the observed TEC.

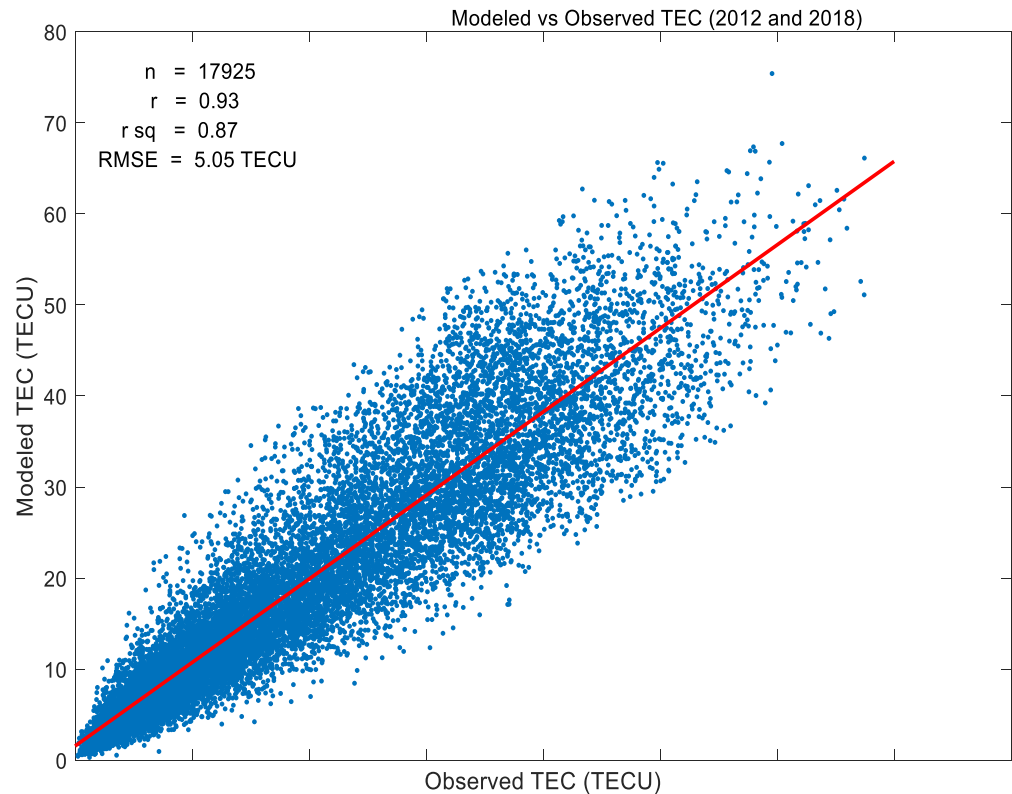


Figure 4. Scatter plot of observed TEC against modeled TEC.

The following observations can be noted from Figure 4. (i) The modeled TEC correlates highly ($r \sim 0.93$) with the observed TEC. (ii) The r squared values indicate that high proportions ($\sim 87\%$) of the variations in the observed TEC can be predicted by the modeled TEC. (iii) The RMSE value of 5.05 TECU signify that the modeled TEC closely approximates the observed TEC.

In order to show that the observed and modeled TEC have similar magnitudes in addition to their similar variation depicted in Figure 4, we computed the differences between corresponding values of the data plotted in the figure. These were referred to as errors. We also computed the percentage of the different errors. The left and right vertical axes in Figure 5 present the distribution of the number of observed errors and their percentages, respectively. It can be seen from the figure, the errors are randomly distributed since the distribution curve is symmetric about 0 TECU. Indeed, the magnitudes of the modeled TEC values are close to that of the observed TEC since the majority of the error values are close to zero.

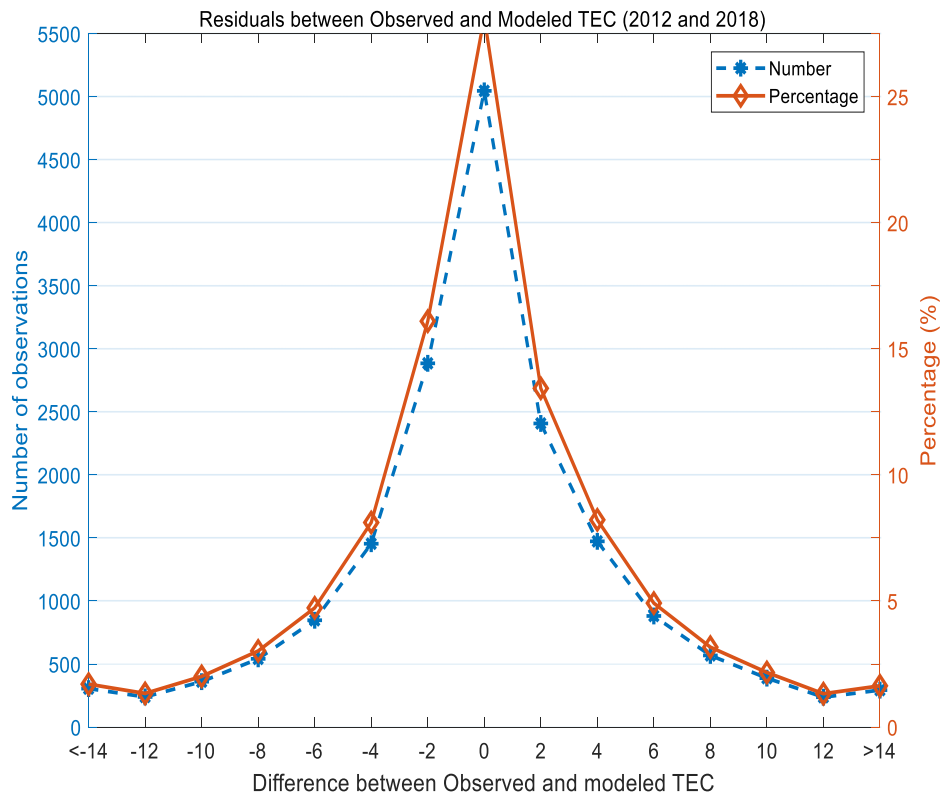


Figure 5. The blue and red curves show the distribution of the number of observed errors (difference between observed and modeled TEC) and the percentage of the errors, respectively.

The cases of high error values (> 10 TECU) mostly have $< 2.5\%$ occurrence probability, as can be seen on the right vertical axis. These high errors may be partly attributed to the

limitation of spline modeling technique (inability to extrapolate) which was discussed earlier in this subsection 5.1.

5.2 Validation using ionosonde TEC measurements

The TEC data measured by the digisonde ionosonde stations over South Africa located at Hermanus, Grahamstown and Louisvale can be accessed from the National Oceanic and Atmospheric Administration (NOAA) website via the link, <ftp://ftp.ngdc.noaa.gov>. The data obtained from the NOAA website is in form of auto-scaled ionospheric parameters such as peak height in F2 layer, critical frequency in F2 layer, and TEC which are stored in Standard Archiving Output (SAO) format files. It should be noted that the TEC data provided in SAO files are obtained by integrating electron density profiles up to altitude of ~700 km. More details about the auto-scaling program (real-time ionogram scaler with true height (ARTIST)) and the electron density profiles they produce can be found in Reinisch and Huang, 2001 and Klipp et al., 2020.

Figure 6 presents with magenta lines the diurnal patterns of TEC measured by ionosonde stations at Hermanus (panels in column (i)), Grahamstown (panels in column (ii)) and Louisvale (panels in column (iii)). The corresponding TEC generated by our spline technique model (spline), NeQuick 2, and IRI-2016 are superimposed with red, green and blue lines, respectively. We need to mention that during computation of TEC using NeQuick 2 and IRI-2016, the height was limited to the approximate altitude of the COSMIC satellites (800 km). Moreover, for the case of IRI-2016, NeQuick model option was specified to estimate topside electron density.

The panels in rows (a) - (c) show TEC on day of year 170 (June), 260 (September), and 350 (December), respectively. All these three days of the year 2013 were geomagnetically quiet. Preliminarily, Figure 6 appears to reveal that IRI-2016 either overestimates (December) or underestimates (June and September) the TEC measured by the ionosonde stations. On the other hand, our spline model and NeQuick 2 seem to depict good correspondence between the observed and the modeled TEC. It can also be seen from Figure 6 that over a particular station, the shape of curves on different days representing TEC generated by the IRI-2016 and NeQuick 2 models are similar. This is expected since these two models were meant to reproduce monthly median values of the ionosphere. This means that our model, based on spline functions may capture better the day-to-day variability of the ionosphere.

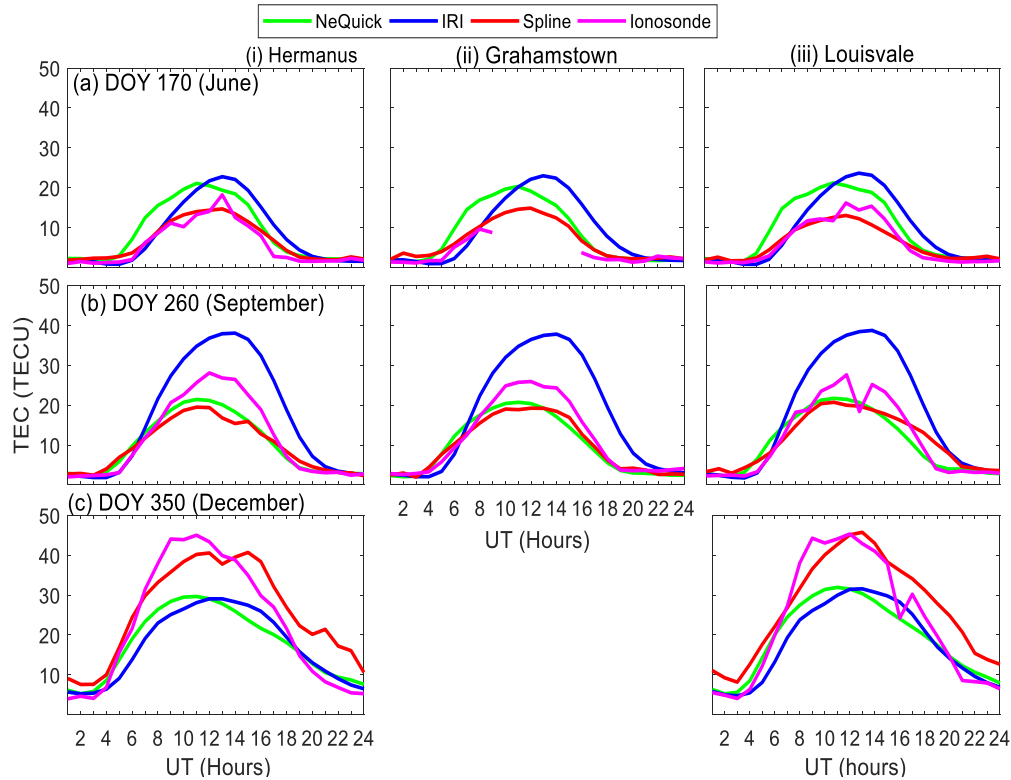


Figure 6: Magenta color shows diurnal TEC observed by ionosonde stations at Hermanus (panels in column (i)), Grahamstown (Panels in column (ii)), and Louisvle (Panels in column (iii)). The green, blue, and red colors show TEC estimations using NeQuick 2, IRI-2016 and Spline models, respectively. Panels in rows (a) - (c) show diurnal TEC during the year 2013 on DOY 170, 260, and 350, respectively.

We generated such data plotted in Figure 6 for geomagnetically quiet days of the entire year 2013 and then performed statistical analysis of the observed and the model TEC data. Table 3 presents in columns 3 the correlation coefficients, r for the correlations between modeled and ionosonde TEC. Moreover, the table presents the RMSE when the ionosonde TEC was estimated using the models listed in column 2. The number of observations, n over each station that were used to determine, r and RMSE are put in brackets below the station name.

Table 3: Correlation coefficients, r and RMSE associated with estimation of TEC observed by ionosonde stations using models

Ionosonde Station /number of observations	Model	R	RMSE (TECU)
Hermanus (n = 5,110)	Spline	0.92	4.64
	IRI-2016	0.86	5.45
	NeQuick 2	0.92	4.10
Grahamstown (n = 4,450)	Spline	0.88	5.56
	IRI-2016	0.82	6.29
	NeQuick 2	0.86	5.27
Louisville (n = 4,543)	Spline	0.94	3.82
	IRI-2016	0.87	5.62
	NeQuick 2	0.94	3.73

It can be seen from Table 3 that the r values associated with NeQuick 2 and spline-based model are consistently better when compared with that of IRI-2016. Moreover, the RMSE values associated with IRI-2016 are the highest in all the cases. These two observations indicate that compared to spline and NeQuick 2, IRI-2016 poorly estimates TEC at the locations of the ionosondes. The RMSE values associated with NeQuick 2 are always slightly lower than that of spline, while the r values associated with spline are mostly comparable or slightly higher than that of NeQuick 2. These discussions demonstrate that our spline model generates TEC values consistently with that observed by ionosondes. This implies that equivalent TEC measured by ionosondes over mid-latitude locations which do not have ionosonde stations can be predicted fairly well using our model. We might validate our model over low-latitude region that falls within the current study area when in future ionosonde observations become available over the region.

5.3 Comparison of our model with existing regional models

It would be good to compare error levels produced when some measured TEC are compared with modeled TEC generated by (i) the existing regional TEC models discussed in section 1 and (ii) our spline technique TEC model. We may not perform such analysis since models in (i) are based on electron density integrated from ground up to GPS satellites (~20,200 km), while model in (ii) is based on electron density integrated up to ~800 km. However, we present Figures 7 and 8 to compare EIA features captured by our spline technique model with those by the neural networks technique of Okoh et al., (2019). The TEC plots based on the neural networks technique can be obtained from MATLAB Central website (Okoh et al., 2019).

(https://www.mathworks.com/matlabcentral/fileexchange/69257-african-gnss-tec-afritec-model?s_tid=prof_contriblnk). We present in Figure 7 examples of TEC generated by neural network model during the year 2012 at 11:00 UT. Over the East African sector ($LT = UT + 3$), this time translates to 14:00 LT and falls within the range of LT when EIA exists over the region (Mungufeni et al., 2018). Panels (a) and (b) in Figure 7 present TEC during March (DOY 81) and September (DOY 260) equinoxes, respectively, while (c) and (d) present during June (DOY 171) and December (DOY 347) solstices, respectively. It is important to mention that these 4 days were geomagnetically quiet.

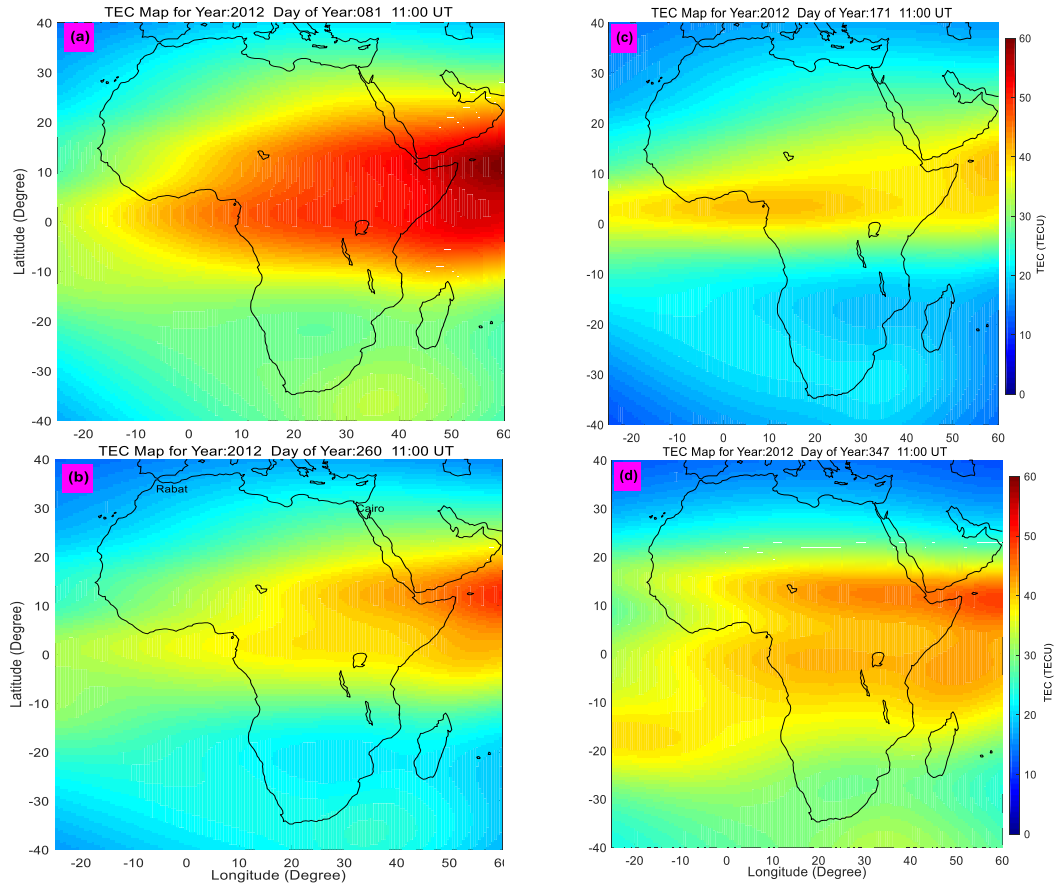


Figure 7: Neural Network TEC maps during the year 2012 at 11:00 UT. Panels (a) and (b) are for March (DOY 81) and September (DOY 260) equinoxes, respectively, while (c) and (d) are for June (DOY 171) and December (DOY 347) solstices, respectively.

In order to generate TEC maps using our model for purposes of comparing with TEC maps in Figure 7, we noted and used the F10.7 flux values on the days indicated in the figure. The TEC maps generated using our model that correspond to TEC maps presented in Figure 7 are presented in Figure 8.

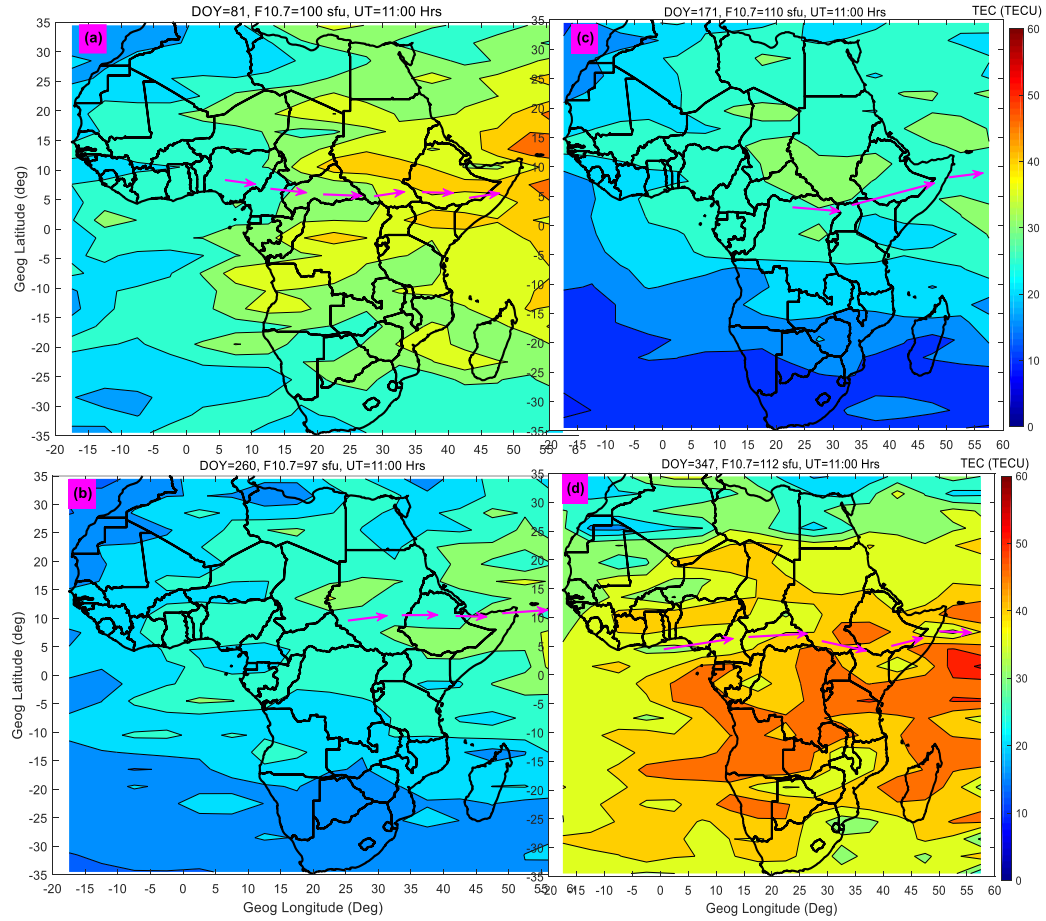


Figure 8: Similar to Figure 7, but generated by spline modeling technique. Magenta arrows indicate approximate locations of EIA trough.

Unlike our TEC maps in Figure 8 which clearly show the EIA trough (see magenta arrows) in all the seasons, the neural network technique TEC maps (Okoh et al., 2019) of Figure 7 only clearly capture the EIA trough in December solstice. As pointed before, this short fall in neural network TEC model might be due to poor amount of data to represent day of year during model development. Another observation that can be made from Figures 7 and 8 is that unlike the neural network model which yields smooth spatial TEC variation, the spline modeling technique does not yield smooth spatial TEC variation. In real life, measurement or observed values rarely vary smoothly. Since the spline modeling technique produces results (see Figure 2) which demonstrate that the modeled data matches almost perfectly the observed data, it is expected that the spatial variations of TEC in maps of Figure 8 are not smooth.

6. Conclusions

This study developed a model of TEC measured by COSMIC satellites. The TEC data were binned according to local time, seasons, solar flux level and spatially. The coefficients of B splines that were fitted to the binned data were determined by means of the least square procedure. As expected, the modeled TEC almost perfectly matched the corresponding observed binned TEC data. The model was validated with independent data that were not used in the model development. The validation revealed that (i) the observed and the modeled TEC correlate highly ($r = 0.93$), (ii) the coefficient of determination R^2 which is the proportion of variance in the observed data predicted by our model was 87 %, and (iii) the modeled TEC closely approximates the observed TEC (RMSE of 5.05 TECU). Due to the extensive input data and the applied modeling technique, we were able to reproduce the well-known features of TEC variation over the African region. Further validation of our model using TEC obtained from ionosonde stations over South Africa at Hermanus, Grahamstown and Louisville reported r values > 0.92 and RMSE < 5.56 TECU. These validation results imply that our model can estimate fairly well TEC that would be measured by ionosondes over locations which do not have the instrument.

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III. Characterizing ionospheric disturbances caused by the North Korean rocket (Hwasong-15) by using a four-dimensional variational (4D-VAR) data-assimilation model

1. INTRODUCTION

The ionosphere consists of ions and electrons whose densities can be sensitively disturbed by various natural and artificial processes [1]. As one artificial disturbing process, rocket flights are known to temper the ionosphere along the rocket's trajectory in terms of the plasma density and the shock signature. The Vanguard 2 rocket was first detected to cause disturbances of the local ionosphere [2]. The analysis of the ionospheric changes caused by the Saturn 5 rocket's exhaust showed that the chemical in the rocket's exhaust better (mainly water vapor and hydrogen molecules) reacted with atomic oxygen ion (O^+) in the ionosphere and that subsequent fast neutralization of the reaction products led to the depletion of the ionospheric density along the trajectory [3].

The ionospheric disturbance by rocket flights has been studied since 1990 by using a dense Global Positioning System (GPS) receiver network. The disturbances caused by Japanese rockets has been detected by using the GPS and compared with the water diffusion model of rocket exhaust [4]. Disturbances caused by North Korean rockets (Taepodong-2 and Taepodong-3) were detected as depletions in the ionosphere's total electron content (TEC) derived from the GPS receivers over Japan [5] and Taiwan [6]. When the allegedly satellite-carrying North Korean rocket (Unha-3) was launched in 2012, the ionospheric disturbances were observed from the Japanese GPS receiver network [7] and the GLONASS receivers for the Russian satellite navigation system [8]. The Korean GPS receiver network reported TEC depletion due to another North Korean rocket flight (Kwangmyongsong-4) in 2016 [9]. A four-dimensional variational (4D-VAR) model has been developed and applied to the reported Korean TEC data to estimate the exhaust emission rate of the Kwangmyongsong-4 rocket [10]. The 4D-VAR model was also able to reconstruct 3D images of the ionospheric hole caused by the rocket's exhaust chemicals, although the rocket's trajectory was far from most of GPS ionosphere pierce points (IPP) and the observed TEC depletion was small. An IPP is the point at which the ionospheric layer (350 km in altitude) is pierced by the radio signal from the GPS satellite on its way to the ground receiver. When the North Korean rocket called Hwasong-15 (H-15) was launched in 2017, the TEC depletion could not be detected in the Korea GPS receiver network because the rocket's trajectory was far from the IPPs of GPS receivers. Fortunately, the TEC depletion

due to H-15 was detected in some of the GLONASS receivers [11]. In this paper, we apply the 4D-Var model, together with a TEC dataset derived from GLONASS receivers in Korea, to characterize the ionospheric disturbances caused by the H-15 flight.

2. METHOD AND DATA

1) The Rocket Trajectory

The H-15 rocket was launched from a North Korean site at 18:17 UT on 28 November, 2017 and reached an altitude of around 4500 km, having covered a horizontal distance of 960 km [11]. The rocket's trajectory is shown with a dashed line in Figure 1, where the red asterisk indicates the launching site, and the curves with the blue and the green labels illustrate the IPP trajectories of GPS and GLONASS receivers with their satellite numbers, respectively. Red dots indicate the receiver sites in Korea, and the Deajeon receiver is marked with a green dot. The GPS IPP trajectories were far from the rocket's trajectory whereas the GLONASS IPP trajectories, especially R 22, were close to the rocket's trajectory. Thus, the TEC data from GLONASS receivers were adopted for analyzing the ionospheric disturbances due to the H-15 rocket's flight.

Because detailed technology information on the H-15 rocket has not been publicized, we assume that the rocket's exhaust consisted of mainly water vapor (H₂O) and hydrogen (H₂) molecules, as suggested for its predecessor, the Teapodong-2 (T-2) rocket [5]. From the approximate trajectory of H-15, the first stage rocket engine was estimated to last up to 100 km in altitude, and the second stage engine was estimated to last up to 450 km in altitude from ~0.5 min to 2.5 min after the launch [11].

2) TEC Data

Global Navigation Satellite System (GNSS) data were obtained from the Korean GNSS network (KGN). The KGN, which has approximately 160 receiver stations, enables spatial and temporal observations. The data are in the RINEX form with a resolution of 30 seconds and are archived at the Korean Astronomy and Space Science Institute (private communication).

The dataset used in this paper is in the form of slant TEC (STEC), which is an integration of the total number of electrons along the line of sight from the transmitter to the satellite receiver. The GPS and the GLONASS STEC values (STEC_P, STEC_L, respectively) are computed using the following relations [11]:

$$STEC_P = \frac{1}{40.308} \times \frac{f_1^2 \times f_2^2}{f_1^2 - f_2^2} [P_2 - P_1], \quad (1)$$

$$STEC_L = \frac{1}{40.308} \times \frac{f_1^2 \times f_2^2}{f_1^2 - f_2^2} [\Phi_1 - \Phi_2 - (\lambda_1 N_1 - \lambda_2 N_2)], \quad (2)$$

where P is the pseudo-range measurement, and Φ_i is the carrier phase measurement of GNSS signals. The parameters N , λ , and f are the initial phase ambiguities, carrier wavelength, and carrier frequency, respectively. The GPS satellites transmit signals at fixed frequencies, $f_1 = 1575.4$ MHz and $f_2 = 1227.6$ MHz. Unlike the GPS satellites, the GLONASS satellites transmit signals at frequencies that vary with the frequency channel number: $k = -7, -6, -5, \dots, 5$, and 6 are used:

$$f_1 = (1602 + k \cdot 0.5625) \text{ MHz}, \quad (3)$$

$$f_2 = (1246 + k \cdot 0.4375) \text{ MHz}. \quad (4)$$

The unit of STEC is TECU, which is defined as 10^{16} el/m². To mitigate the multipath effects, we computed the STEC values only for satellites with elevation angles greater than 30°. As shown in Figure 1, the GLONASS IPP trajectories (R13 and R22) were near to the rocket's trajectory; thus, the data from R13 and R22 were adopted every 30 sec for the entire assimilation period of 40 min. Thus, STEC_L values (GLONASS STEC) computed with Eq. (2) are utilized in this paper.

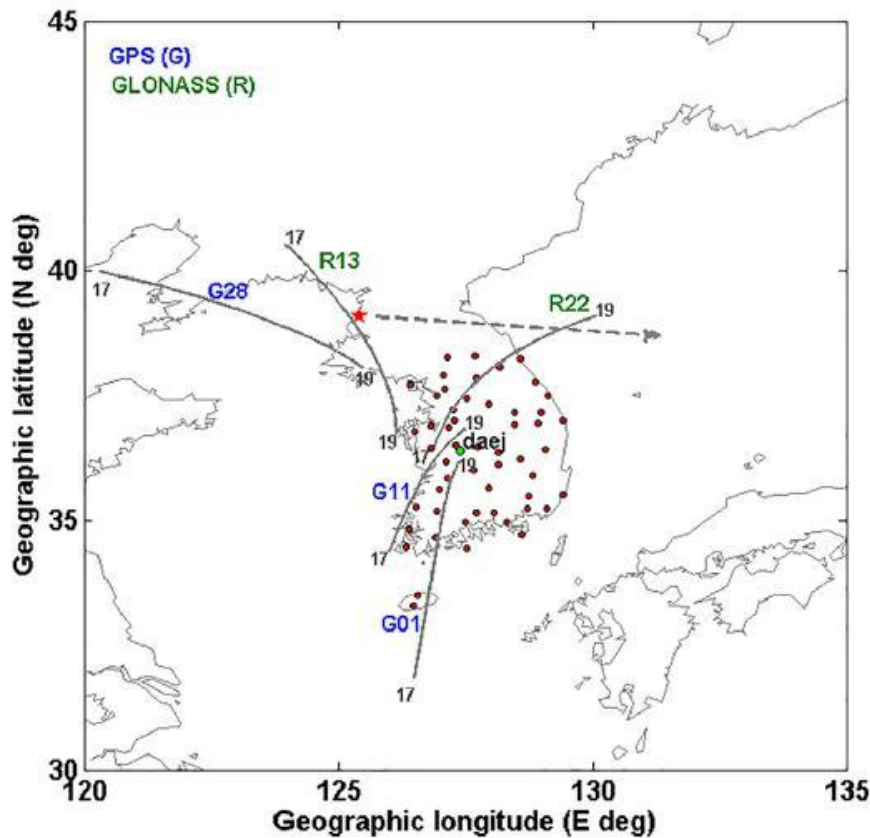


Figure 3. Geometry of the rocket's trajectory and the GNSS ground tracks. The red asterisk indicates where the rocket was launched, and the dashed line indicates the trajectory of the rocket. The blue and the green labels illustrate the GPS and the GLONASS satellite numbers, respectively. The solid gray curve represents the satellite's ionosphere pierce point (IPP). Red dots and green dot indicate the GNSS receivers and the Deajeon receiver. The number on the satellite IPP (17,19) shows the universal time when the satellite IPP passes [11].

3) Preprocessing

Before using the GLONASS STEC data in the assimilation model, we compared them with those STEC values computed from an empirical ionospheric model, the IRI 2016 model, which is the most recent version of a widely used model. The IRI 2016 model is also utilized as the background model for the 4D-VAR assimilation. Some examples for the STEC between GLONASS 13 and the IRI model are presented in Figure 2. The red and the blue curves represent the GLONASS STEC and the IRI computed STEC values, respectively. The dashed vertical line marks the H-15 rocket's launch time. The GLONASS STEC curves clearly show electron depletion after the rocket's launch whereas the IRI STEC curves are smoothly varying, as expected, without any abrupt changes after the rocket's launch.

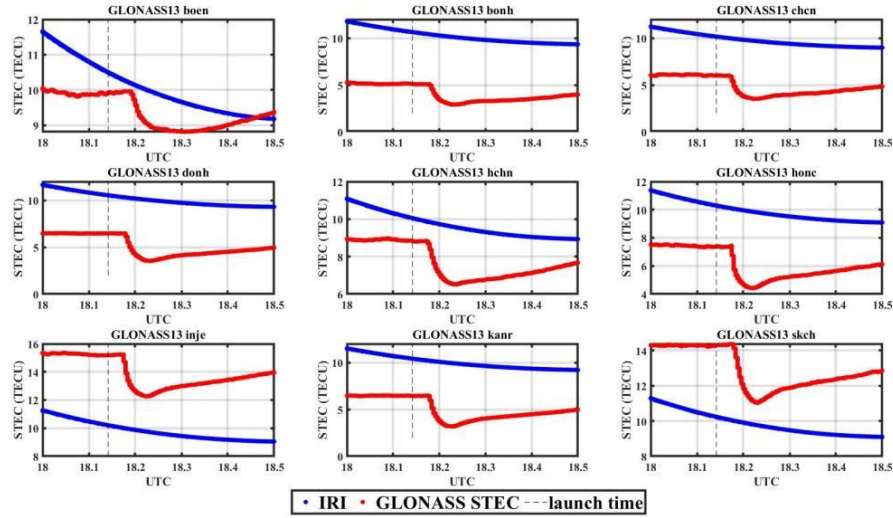
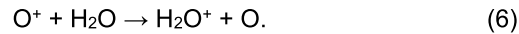


Figure 2. Variations in the STEC between GLONASS satellites and the receiver station. The x- and the y- axis are the time in UTC and the STEC in TECU, respectively. The satellite number (GLONASS 13) and the station name are label on the top of each plot. The red and the blue lines represent the GLONASS STEC data and IRI model STEC values, respectively. The dashed line denotes the launch time.

However, significant differences exist between the GLONASS STEC's and the IRI STEC's even before the rocket's launch. The average difference and its standard deviation at the launch time were 0.56 and 3.78 TECU, respectively. The STEC difference originates from many sources of uncertainties, including receiver biases in the GLONASS TEC computation [12]. Because the 4D-VAR assimilation utilizes the IRI 2016 as the background model, we shifted the GLONASS STEC values to the IRI STEC values by simply adding or subtracting the difference at the launch time.

4) Chemical reduction of the electron density

The rocket's exhaust chemicals were assumed to consist of water (H_2O) and hydrogen (H_2) molecules, which react with atomic oxygen ions (O^+) in the ionosphere:



The product ions of these reactions quickly become neutrals through a dissociative recombination process at a rate of $\sim 10^{-7} cm^3 s^{-1}$, as in the following reactions:





Because the recombination rates are fast, the loss rate of ionospheric O^+ is determined effectively by the reaction rates of Eqs. (5) and (6), whose rate coefficients are $K^{\text{H}_2} = 2.0 \times 10^{-9} \text{ cm}^3\text{s}^{-1}$ and $K^{\text{H}_2\text{O}} = 2.2 \times 10^{-9} \text{ cm}^3\text{s}^{-1}$, respectively [3,10,13]. Even these reaction coefficients are ~ 1000 times faster than the reaction with N_2 ($K^{\text{N}_2} = 7 \times 10^{-13} \text{ cm}^3\text{s}^{-1}$), which is the major loss reaction in the normal ionospheric F region. Hence, the water and the hydrogen molecules in the rocket's exhaust cause depletion of O^+ (and electrons) in the ionosphere, resulting in a depletion hole along the rocket's trajectory.

5) Modeling of the ionospheric hole

When the rocket's exhaust chemicals are deposited in the ionosphere, the exhaust chemicals diffuse away from the rocket's trajectory with time. The diffusion coefficients of the rocket's exhaust water and hydrogen molecules are important parameters for modeling a realistic distribution of these molecules as a function of time and space. The diffusion coefficients depend on temperature and density in the background neutral atmosphere and, thus, vary with altitude. The diffusion coefficients at three altitudes, as given in Table 1, were adopted from the literature [3, 4]. When the ionospheric hole along the rocket's trajectory is modeled, the diffusion coefficients are interpolated linearly between the altitude intervals in the Table 1 at every 20-km altitude bin.

Table 1. Water and hydrogen diffusion coefficients at different heights

Height (km)	$D^{\text{H}_2\text{O}} (\text{km}^2\text{s}^{-1})$	$D^{\text{H}_2} (\text{km}^2\text{s}^{-1})$
250	2	6
350	12	39
450	67	210

The distributions of the rocket's exhaust chemicals in the atmosphere generally follow the diffusion and advection equation [14]:

$$\frac{\partial n}{\partial t} = -\nabla \cdot (Un) + \nabla \cdot D\nabla n + E_0\delta(t) \quad , \quad (10)$$

where n is the deposited density, U is the atmospheric advection velocity, D is the diffusion coefficient, and E_0 is the emission at $t = 0$. Here, we set the time as $t = 0$ when the rocket deposits instantaneously the exhaust chemical at each point along the trajectory, thus expressing the emission rate as a delta function. At ionospheric altitudes, the advection term

can be ignored because the diffusion term is dominant. Further, if the emissions are assumed to have spherically symmetric diffusion, Eq. (10) is reduced to

$$\frac{\partial n}{\partial t} = D \nabla^2 n = \frac{D}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial n}{\partial r} \right) + E_0 \delta(t). \quad (11)$$

The solution of this simple diffusion equation is known to be

$$n(r, t) = \frac{E_0}{(\sqrt{4D\pi t})^3} \exp \left(-\frac{r^2}{4Dt} \right), \quad (12)$$

where r is the position relative to the emission source and t is the time elapsed after the instantaneous emission at a specific point along the trajectory [10].

Figure 3 shows the information on the modeling of $n(r, t)$. The blue solid line indicates the rocket's trajectory, and the blue dot specifies the rocket's position along the trajectory every 10 seconds. The emission of exhaust is assumed to be concentrated instantaneously at these blue dot points with the sum of exhaust during the 10-second period. The concentration of water or hydrogen molecules at a specific position and time is computed by adding up the exhaust chemical diffusing from these dots during the time after the instantaneous deposition at those blue dot positions. The dotted lines represent the distance (r) between a specific position and the emission points (blue dots) along the trajectory. The rocket's second stage is assumed to burn at altitudes of 100 - 450 km, and the corresponding horizontal distances are marked with the green dashed lines.

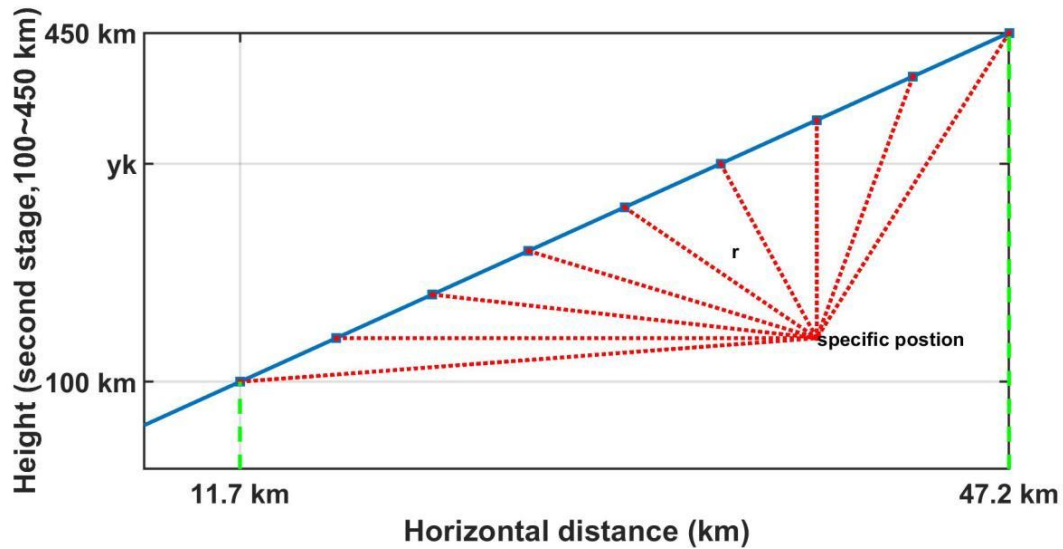


Figure 3. Computation geometry of diffusing rocket's exhaust chemicals. The x- and the y-axis represent the horizontal distance and the height, respectively. The blue line shows the rocket's trajectory with blue dots at every 10 seconds. The red dotted lines

are diffusing distances between blue dots and a specific position. The 4D-VAR model runs for the rocket's second stage (100 km to 450 km), and the green dashed lines denote the projected horizontal distances.

The rate of electron density change in the ionosphere can be expressed using the production rate from photoionization, the loss rate due to reactions with thermospheric molecules and the loss rate due to reactions by the rocket's exhaust chemicals (reactions 5, 6) as follows:

$$\frac{dX}{dt} = cX_b - cX - \beta X = cX_b - (c + \beta)X, \quad (13)$$

where X is the electron density, X_b is the background electron density, and β is the average loss rate coefficient with $\beta = n(r,t)^{H2O} K^{H2O} + n(r,t)^{H2} K^{H2}$. In the normal ionospheric F region, the production rate by photoionization (cX_b) is balanced by the loss rates, cX , by the reactions



with rate coefficients of $K^{N2} = 7 \times 10^{-13} \text{ cm}^3/\text{s}$ and $K^{O2} = 8 \times 10^{-12} \text{ cm}^3/\text{s}$, respectively [15]. Thus, the loss rate coefficient, c , can be computed as $c = n(O_2)K^{O2} + n(N_2)K^{N2}$. The number densities of O_2 and N_2 at each altitude are adopted from the MSISE-90 model [16].

The physically meaningful solution of Eq. (13) can be expressed as

$$X = \frac{X_b}{c + \beta} (c + \beta e^{-(c + \beta)t}). \quad (16)$$

In this solution, the electron density starts with X_b just before the rocket's flight ($t = 0$), and decreases with a rate $e^{-(c + \beta)t}$, and finally recovers to X_b as the water and the hydrogen molecules in the rocket's exhaust spread away ($\beta \rightarrow 0$). Note that this equation is the improved chemical model from a previous work [10].

6) The 4D-VAR

An optimal estimate of the current ionospheric state can be obtained by combining observations and physical model predictions. The four-dimension variational (4D-VAR) method utilizes a minimization of the cost function that is expressed with unknown parameters in space and time domain as follows:

$$J(X_0, X_k, E_0^{H_2O}, E_0^{H_2}) = \frac{1}{2} ((E_0^{H_2O} - E_b^{H_2O})^T (Q^{H_2O})^{-1} (E_0^{H_2O} - E_b^{H_2O}) + (E_0^{H_2} - E_b^{H_2})^T (Q^{H_2})^{-1} (E_0^{H_2} - E_b^{H_2})) + \frac{1}{2} ((X_0 - X_b)^T B^{-1} (X_0 - X_b)) + \frac{1}{2} \sum_{k=0}^{k=N} (H_k X_k - Y_k)^T R_k^{-1} (H_k X_k - Y_k). \quad (17)$$

The cost function is the sum of squared differences between unknown parameters and model predictions: the unknown parameters are the rocket's emission rates of H₂O ($E_0^{H_2O}$) and H₂ ($E_0^{H_2}$), the electron density at t_0 (X_0) and the electron density (X_k); the corresponding model predictions are $E_b^{H_2O}$, $E_b^{H_2}$, and X_b , and observation values are STEC (Y_k). The subscript k runs with the time step after t_0 within a data-assimilation window (2.5 min). The squared differences are expressed with the error covariances for emission rates (Q^{H_2O} and Q^{H_2}), the error covariance for background electron density model (B), and the error covariances for the observed STEC at time k (R_k). Finally, the observed STEC values (Y_k) are related to the electron density through the geometry matrix at time k , as $Y_k = H_k X_k$. All the covariance matrices were adopted from the previous work and are listed in Table 2 [10].

Table 2. Covariance matrices used in the analysis

Matrix	Expression	Dimension
B	$\text{Diag}(X_b^2) \times 3 \times 10^{-6}$	$P \times P$ (P: number of elements)
R_k	$(Y_k^2) \times 0.001$	$M \times M$ (M: number of elements)
Q^{H_2O}	$(3 \times 10^{23})^2$	1×1
Q^{H_2}	$(3 \times 10^{23})^2$	1×1

Finding the minimum of the cost function is equivalent to searching for the optimal parameters satisfying $\nabla J = 0$, which can be reduced to a constrained problem by using an augmented Lagrangian function [10]:

$$L(X_0, X_k, E_0^{H_2O}, E_0^{H_2}, \lambda_k) = J(X_0, X_k, E_0^{H_2O}, E_0^{H_2}) + \sum_{k=0}^n \lambda_k^T g(X_k) \quad (18)$$

$$g(X_k) = (X_k - X_{k-1} (1 - \beta(t_k) dt)).$$

At extreme $\nabla_w L = 0$ and $w = X_0, X_k, E_0^{H_2O}, E_0^{H_2}$ with a boundary condition of $\lambda_{N+1} = 0$, variational calculus can be used to derive the following relations [14,17]:

$$\lambda_N = H_N^T R_N^{-1} (Y - H_N X_N), \quad (19)$$

$$\lambda_k = \left\{ \frac{\partial(X_{k+1})}{\partial X_k} \right\}^T \lambda_{k+1} - \mathbf{H}_k^T \mathbf{R}_k^{-1} (\mathbf{H}_k X_k - Y_k), \quad (20)$$

$$E_0^{H_2O} = E_b^{H_2O} - \mathbf{Q}^{H_2O} \sum_{k=0}^{N-1} \left\{ \frac{\partial(X_{k+1})}{\partial E_0^{H_2O}} \right\}^T \lambda_{k+1}, \quad (21)$$

$$E_0^{H_2} = E_b^{H_2} - \mathbf{Q}^{H_2} \sum_{k=0}^{N-1} \left\{ \frac{\partial(X_{k+1})}{\partial E_0^{H_2}} \right\}^T \lambda_{k+1}, \quad (22)$$

$$X_0 = X_b + \mathbf{B} \lambda_0. \quad (23)$$

The initial step in the computation starts with λ_N from the model X_N predicted using Eq. (19). Thus, the model should first predict all X_k 's for $k = 0, 1, \dots, N$ within the assimilation window (2.5 min). Then, all λ_k 's can be computed down to λ_0 ; thus, a new X_0 can be used in the next iteration. Note that the prediction model expressed in Eq. (20) should provide the Jacobian matrix $\frac{\partial X_{k+1}}{\partial X_k}$ to compute X_k 's from X_0 . The iteration is terminated when the gradient of the update $(\mathbf{B}^{-1}(X_0 - X_b) - \lambda_0)$ is less than a set tolerance.

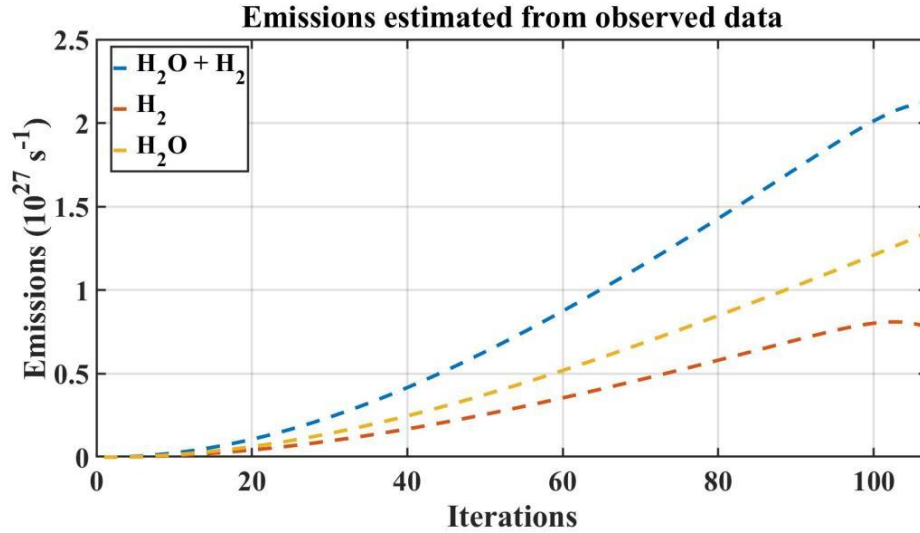


Figure 4. Estimated emission rates of H₂ and H₂O molecules in the rocket's exhaust as the number of iterations increases. The emission rates have units of 10²⁷ molecules/s. Note that the emission rates start with zero value.

3. RESULTS AND DISCUSSION

The 4D-VAR iteration described above started with no emission rates

($E_b^{H_2O} = E_b^{H_2} = 0$) because no priori information was available. However, as the iteration repeated, the observed information in terms of STEC values was fed to estimate the emission rate through Eqs. (19) – (22). As shown in Figure 4, the estimated emission rates monotonically increase as the iteration continues until a sign of saturation appears around 100 iterations. However, saturation of the H_2O emission rate is not clear even after 108 iterations. Note that the emission rates are in 10^{27} molecules/s, which is a reasonable magnitude of emission for a comparable size rocket [5]. Finding the optimal solution from the 4D-VAR method requires a practical criterion to terminate the iteration, which can be obtained from an analysis of the convergence of the solution to the observed constraint.

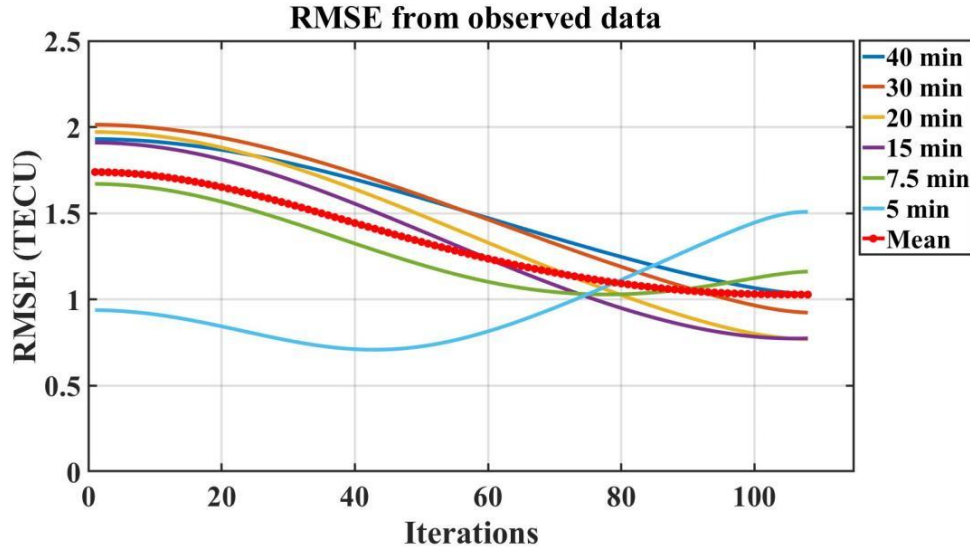


Figure 5. Root-mean-square error (RMSE) between the observed STEC's and the 4D-VAR estimates at various times after the launch.

Figure 5 displays the root-mean-square error (RMSE) as the number of iterations increases. Here, the RMSE is defined as the root mean squared difference between the observed STEC and the computed STEC in the given assimilation window. For most of the assimilation windows, the RMSE decreases monotonically all the way up to 108 iterations, but the RMSEs for early assimilation windows (5 and 7.5 minute after the H-15 launches) increase after 60 and 80 iterations, respectively. The averaged RMSE over all assimilation windows decreases monotonically up to ~108 iterations and stagnates thereafter. The convergence of the iteration can be evaluated with the norm2 of the relative difference between new and old states, $\|(X_{new} - X_{old})/X_{old}\|_2$. Figure 6 presents the behavior of the norm2

difference with the number of iterations for various epochs. Unlike the RMSE in Figure 5, the updated differences for all epochs decrease up to the iteration number 108. Thus, we adopt the 4D-VAR results at 108 iterations as a practical optimal solution. In this practical solution, the total rocket emission rate is estimated to be $2.1 \times 10^{27} \text{ s}^{-1}$, of which approximately 60% is H_2O and the rest H_2 . The estimated emission rates are comparable to the estimates for another North Korean rocket (K-4) [10].

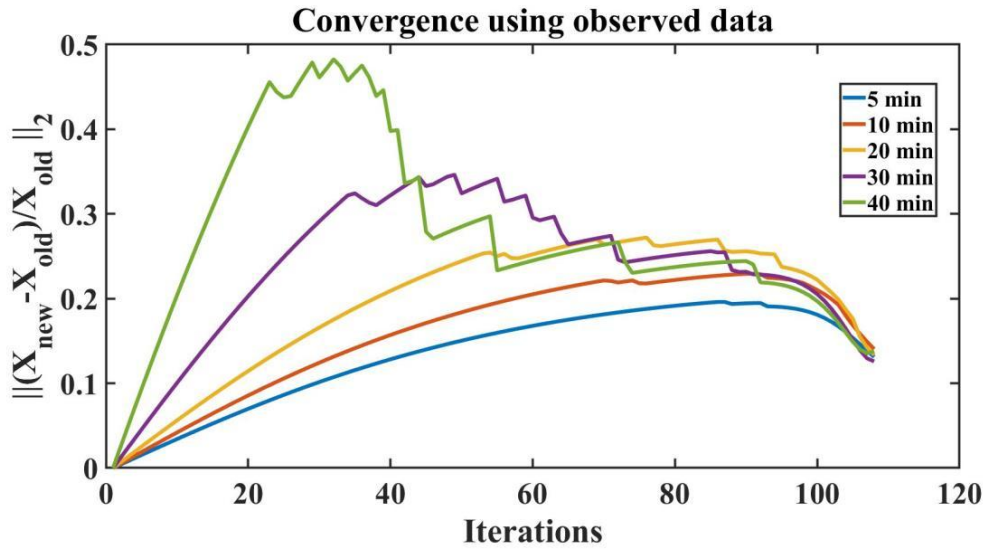


Figure 6. The norm 2 of the relative difference between old and new states, $\|(X_{\text{new}} - X_{\text{old}})/X_{\text{old}}\|_2$, at each iteration for various time epochs. Note that the update starts to become small for all epoch around a little more than 100 iterations.

To evaluate the confidence of the estimated emission, we simulated the ionospheric holes for five emission values ($E_0 = 2.5, 4.5, 6.5, 8.5$, and $10.5 \times 10^{26} \text{ s}^{-1}$) by using Eq. (16). In all the simulation, the ratio between water and hydrogen molecules in the emission was set as 6 to 4. Then, we estimated back the emission values by applying the 4D-VAR model to the STEC data that had been computed from the simulated ionospheric hole with the same geometry as in the actual GLONASS STEC data. The estimated emission values are listed in Table 3, where the input emission values are denoted with subscript “o” (E_o) and the estimated values are without the subscript (E). The emission values estimated by using the 4D-VAR model are quite close to the input values, with a relative mean difference of 0.6 percent. Thus, the simulation demonstrates that the estimated rocket emission

of $2.1 \times 10^{27} \text{ s}^{-1}$ from GLONASS STEC data is confident within ~ 1 percent.

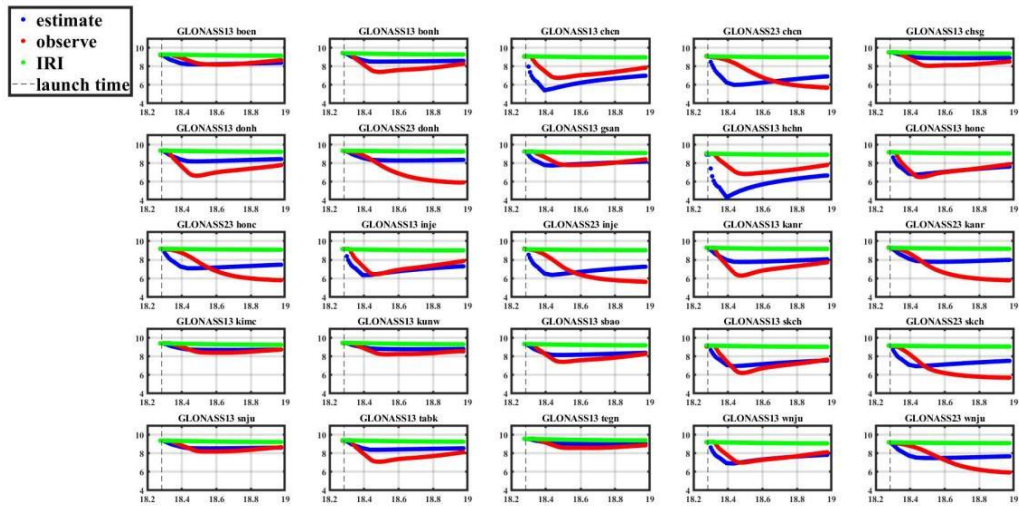


Figure 7. Comparison of the 4D-VAR estimate and the GLONASS STEC along with the IRI model STEC. In each plot, the x-axis and the y-axis represent time in UT (universal time) and slant total electron contents (STEC) in units of TECU ($1 \text{ TECU} = 10^{16} \text{ electron/m}^2$). The dashed line represents the time at 18.3 UT when the North Korean rocket (H-15) was launched. The GLONASS satellite numbers and the receiver station names are labeled at the top of each plot.

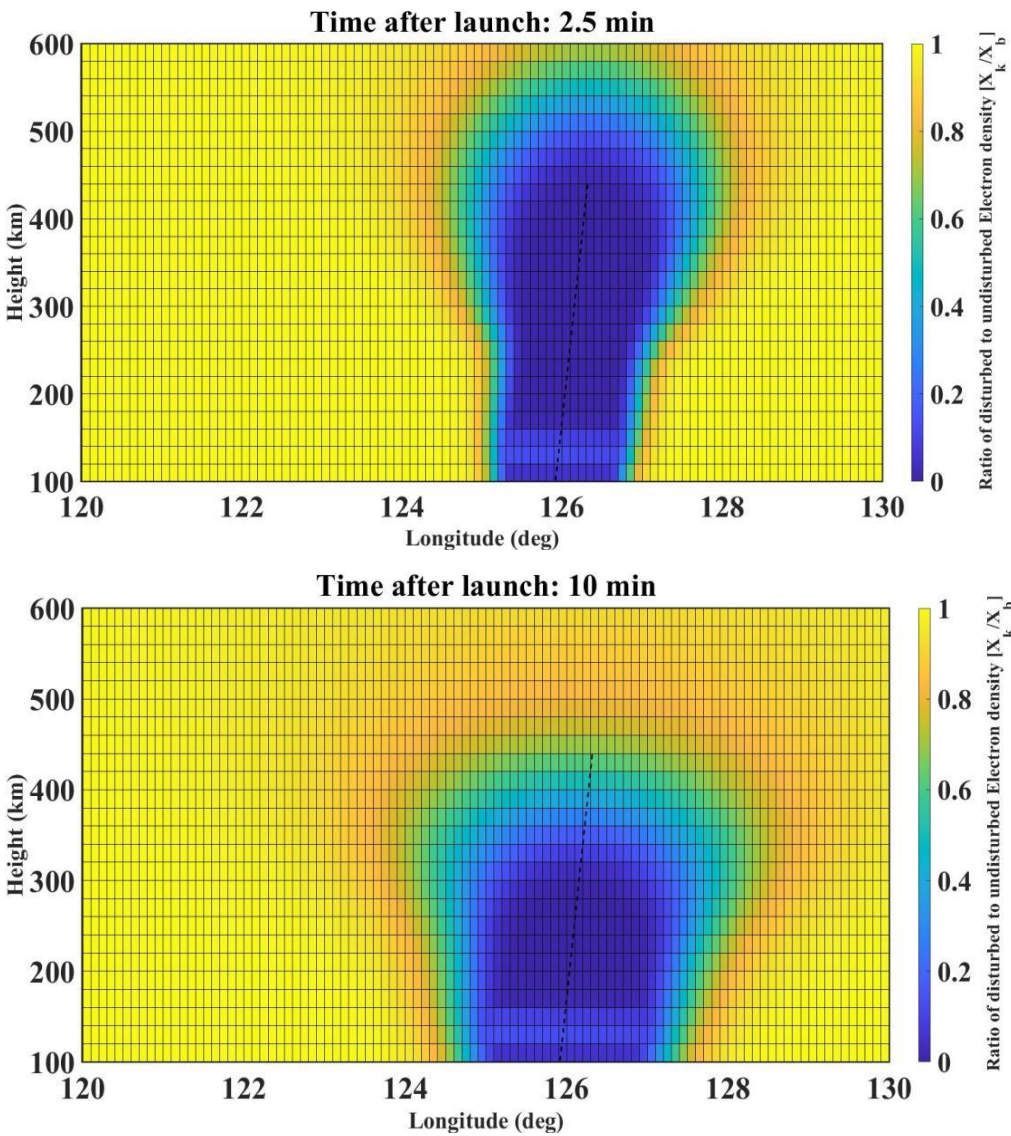
Table 3. Simulation of ionospheric holes to evaluate the confidence of the estimated emission

E_o (10^{26} s^{-1})	$E_o^{H^2}=0.4 \times E_o$	E^{H^2}	$(E^{H^2}-E_o^{H^2})/E_o^{H^2}$	$E_o^{H^{2O}}=0.6 \times E_o$	$E^{H^{2O}}$	$(E^{H^{2O}}-E_o^{H^{2O}})/E_o^{H^{2O}}$	$E=E^{H^2+}E^{H^{2O}}$	$\text{abs}(E-E_o)/E_o$
2.5	1.0	1.02	0.02	1.5	1.46	-0.02	2.49	0.006
4.5	1.8	1.85	0.03	2.7	2.65	-0.02	4.50	0.001
6.5	2.6	2.69	0.03	3.9	3.85	-0.01	6.54	0.006
8.5	3.4	3.53	0.04	5.1	5.06	-0.007	8.59	0.010
10.5	4.2	4.29	0.02	6.3	6.16	-0.02	10.4	0.005
Relative mean difference			0.028			-0.016		0.0056

Figure 7 presents a comparison of the STEC estimate from the adopted solution to the GLONASS STEC values at 25 stations. The IRI model STEC values are also over-plotted with a green curve to mark the undisturbed ionosphere. Although the STEC estimates from the adopted solution do not perfectly match the GLONASS STEC values, the adopted solution reconstructs reasonably well the

general behavior of the ionospheric depletion due to the rocket's exhaust chemicals.

The ionospheric hole due to the rocket's exhaust chemicals is displayed on the altitude-horizontal plane containing the rocket's trajectory (roughly along the



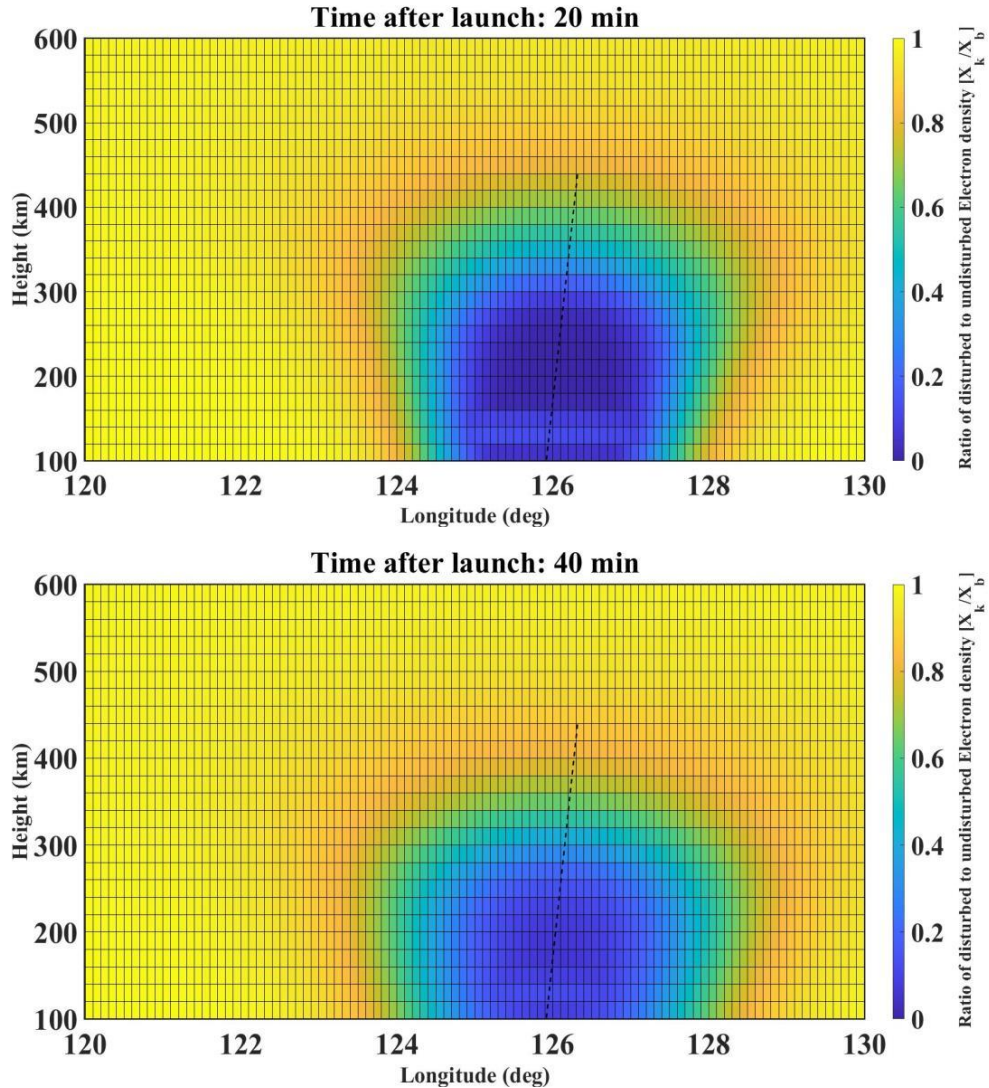


Figure 8. Color contour plots of the ionospheric hole estimated from the 4-VAR model. The rocket's trajectory is denoted with a dashed line, which lies roughly along a latitude of 39°.

latitude of 39°) in Figure 8. The dotted line denotes the trajectory of the rocket's second stage, which passes through the ionosphere F region from 100 km to 450 km in altitude. The grid of the longitude increased by 0.1° from 120° to 130°, and the height increased by 20 km from 100 km to 600 km. The color scale is the ratio of the disturbed electron density (X_k) at a specific time to the undisturbed background electron density (X_b). As the rocket's exhaust water and hydrogen molecules diffuse in the ionosphere, an electron depletion clearly appears along the trajectory. Over time, the depletion becomes low and spreads widely. Note that a slight mitigation of the depletion within the hole appears in the altitude range of 120 - 160 km because

the undisturbed background electron density (X_b) is minimized between the E and the F1 layers.

4. CONCLUSION

In this study we reconstructed the ionospheric hole caused by the exhaust chemicals from the North Korean rocket Hwasong-15 by assimilating STEC data from the Korean GNSS receiver network into a 4D-VAR model. The rocket H-15 was launched on 28 November 2017 at 18:17 UT, passed the ionosphere briefly and reached an altitude around 4500 km [11]. The rocket's exhaust water and hydrogen molecules deplete the ionospheric electron density significantly along the trajectory, resulting in an ionospheric hole, which was noted in the GNSS STEC data. With a standard diffusion model for the rocket's exhaust water and hydrogen molecules, the 4D-VAR model not only reconstruct the ionospheric hole noted in the GNSS data, but also confidently estimates the rocket's exhaust emission rate to be $\sim 2.1 \times 10^{27}$ molecules per sec with a ratio 2:1 of water to hydrogen. The 4D-VAR model in this study updates the previous work [10] by including a new chemical model Eq. (16) and, thus, in the future, can be readily used to analyze the ionospheric disturbances caused by various rocket flights.

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IV. A regional ionospheric assimilation study with GPS and COSMIC measurements using a 3D-Var algorithm (IDA4D)

1. Introduction

Numerous data assimilation methods have been developed and used in many research and application fields such as meteorology, oceanography, and seismology. Data assimilation is a method of improving the performance of a physical or empirical model by assimilating the observational data into the model (Botto et al., 2018; Bouttier and Courtier, 1999; Ghil and Malanotte-Rizzoli, 1991; Reichle, 2008; Talagrand, 1997). In recent years, data assimilation techniques are often used in the three-dimensional (3-D) study of electron density in the fields of the ionosphere and space science (Aa et al., 2016; Yue et al., 2012). As the necessity of the 3-D electron density structure of the ionosphere has emerged in many fields, empirical models and physics-based models, such as International Reference Ionosphere (IRI), NeQuick, and Thermosphere-Ionosphere-Mesosphere Electrodynamics–General Circulation Model (TIME-GCM), have been developed in the global scale (Bilitza, 2002; Bilitza et al., 2017; Radicella, 2009; Roble and Ridley, 1994). However, since the ionosphere varies with time and space in many scales, the global models need to be refined by assimilating observed data that reflect temporal and spatial variations as detail as possible.

To date, various types of ionosphere data assimilation schemes have been developed (e.g., Angling and Khattatov, 2006; Aa et al., 2016; Bust et al., 2001, 2004, 2007; Bust and Datta-Barua, 2014; Lee et al., 2012; McNamara et al., 2011; Mehta et al., 2018; Pezzopane et al., 2013; Pi et al., 2003; Pignalberi et al., 2019; Scherliess et al., 2004; Schunk et al., 2004; Ssessanga et al., 2018; Thompson et al., 2006; Yue et al., 2007; Wang et al., 2004). For example, McNamara et al. (2007, 2011) used an assimilation model called Global Assimilation of Ionospheric Measurements - Gauss-Markov (GAIM-GM) to ingest Global Navigation Satellite System (GNSS) derived total electron content (TEC) and Digisonde electron density profile data and compared them with observations. Pezzopane et al. (2011, 2013) carried out assimilation with real-time 3-D IRI model. Recently, Pignalberi et al. (2019) presented an assimilative technique of updating the IRI model using GNSS-derived vertical TEC observations. Among them, a three-dimension variational (3D-var) algorithm, which has been widely utilized in meteorological models, was adopted to the ionospheric data assimilation by Bust et al. (2004), and named as IDA3D (Ionospheric Data Assimilation Three-Dimensional). Later, the IDA4D (Ionospheric Data Assimilation Four-Dimensional) model was developed using the Gauss-Markov Kalman Filter (GMKF) in

the time sequence data (Bust et al., 2007). A current version of the IDA4D code is designed to accommodate different types of observational data for assimilation, such as total electron content (TEC), HF radar data, occultation data, optical observation data, and ionosonde data.

Azeem et al. (2015) utilized the IDA4D code to study the global ionospheric response to the 2009 sudden stratospheric warning (SSW). Nicolls et al. (2009) presented an alternative approach for estimating the E region density profiles from radio occultation measurements of COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate) and from F region density obtained by IDA4D. Mengist et al. (2018, 2019) assessed the performance of IDA4D by assimilating multiple data types over the Korea peninsula and vicinities. Independently, Ssessanga et al. (2019) have developed a four-dimensional variational (4D-var) algorithm to estimate the 3-D structure of the South African regional ionosphere using STEC data from Global Navigation Satellite System.

As a follow-up study to Mengist et al (2019), the purpose of this study is to evaluate the performance of the IDA4D model in estimating the regional ionosphere around the Korean Peninsula by utilizing GPS STEC and COSMIC data. Section 2 introduces the types of data used in the data-assimilation and for validation, and describes the IDA4D scheme briefly. In sections 3, data-assimilation results are presented and discussed according to the combinatorial cases of multiple data types. The summary and conclusion are given in section 4.

2. Data and Methodology

2.1 GPS-TEC

The GPS satellites orbiting the Earth at an altitude of about 20,200 km, are distributed in six orbital planes, and transmit navigation signals constantly. The signals of the L1 (1575.42MHz) and L2 (1227.60MHz) frequencies from the GPS satellites pass through the ionosphere and are received by ground-based GNSS receivers. Along the signal path slant total electron contents (STEC) in the ionosphere can be derived from the difference in time delay between the two frequencies and vertical total electron contents (VTEC) can be converted from STEC's. A global TEC dataset from a registered network of ground-based receivers is available on University NAVSTAR Consortium (UNAVCO) network (<ftp://data-out.unavco.org>). These data can be downloaded in RINEX form at a resolution of 30 second. According to Pignalberi et al. (2021), the vertical TEC value may be dependent on the calibration method. We computed TEC values by using GOPI software (<https://seemala.blogspot.com/2017/09/gps-tec-program-ver-295.html>). The GOPI program calculates the TEC assuming a thin shell ionosphere at an altitude of 350 km. To avoid the multi-path effects near the horizon, we selected TEC data with the elevation angles of the GPS rays higher than 30°.

Lee et al (2013) analyzed GPS TEC measurements by the JASON-1 satellite orbiting at the altitude of 1,336 km, and reported the average plasmaspheric TEC of 3 TECU ($1 \text{ TECU} = 10^{16} \text{ electron/m}^2$) between the JASON-1 (1,336km) and GPS satellites (20,200 km) for mid-latitudes. By adopting this average plasmaspheric TEC value, we calibrate the GPS-TEC from UNAVCO by subtracting the plasmaspheric TEC contribution, as in Eq. (1), where El_i is the elevation angle corresponding to the signal path of the GPS-TEC.

$$\text{Calibrated GPS-TEC}_i = \text{GPS-TEC}_i - \frac{3 \text{ TECU}}{\sin(El_i)} \quad (1)$$

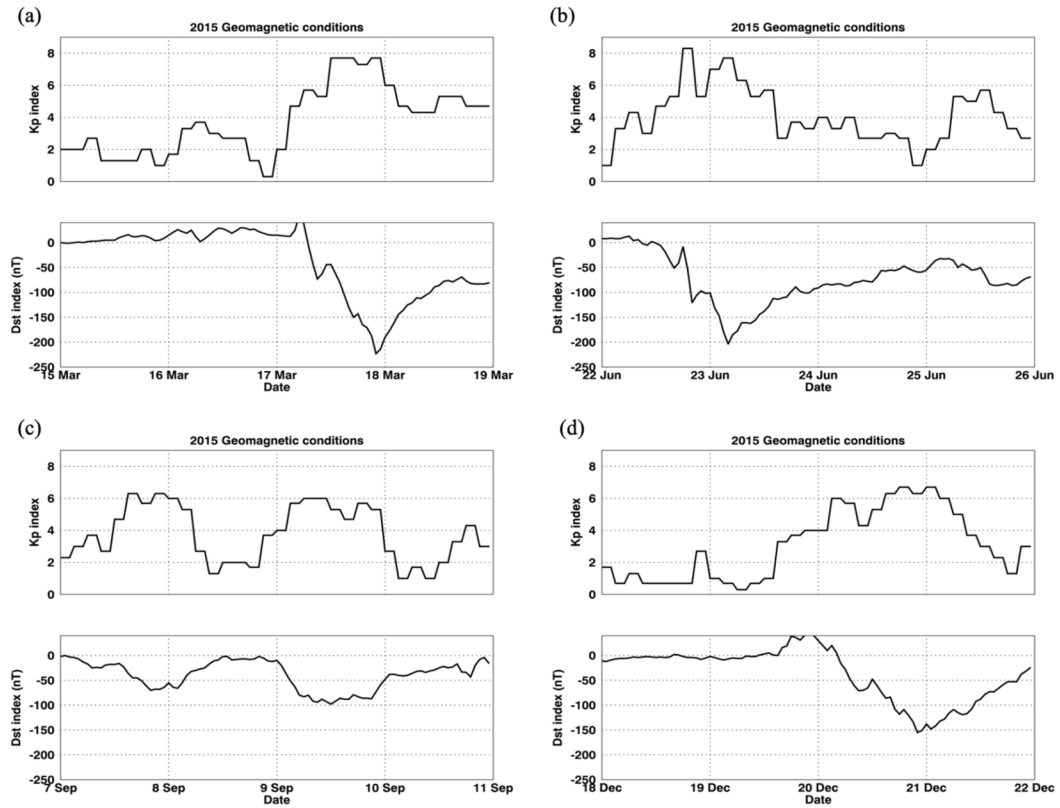


Fig. 1. The geomagnetic conditions (Kp index (top), Dst index (bottom)) for the test periods of March (a), June (b), September (c), and December (d) in 2015.

Thus, the top boundary of our assimilation model is the JASON-1 altitude, 1336 km.

2.2 COSMIC/RO

Radio occultation (RO) from a satellite is also a remote sensing technique for observing the physical characteristics of the atmosphere using GNSS signals. It is based on the phenomenon that GNSS radio waves are refracted and delayed by the atmosphere. The

FORMOSAT-3/COSMIC satellite, jointly developed by the U.S and Taiwan in 2006, provides more than 2,500 RO data per day. The electron density profiles from the RO data have been provided by COSMIC Data Analysis and Archive Center ((CDAAC), <http://cdaac-www.cosmic.ucar.edu/>). For this research, we used the second level data, called "ionprf", that contain the maximum electron density of the F2 layer (NmF2). The NmF2 data extracted from the RO electron density profiles can present spatial smearing due to the latitudinal gradient in the ionosphere. In order to eliminate the smearing effect, we excluded NmF2 data whose occultation traces were farther than the ionospheric spatial correlation length of 1,500 km, based on previous papers (Krakowski et al., 2011; Mengist et al., 2019; Yue et al., 2007). Pignalberi et al. (2020) did a similar selection by setting latitude-longitude limitation of RO traces. In addition, the COSMIC-STECh data were obtained from the level 1b data called "podTec". In this study, the total numbers of

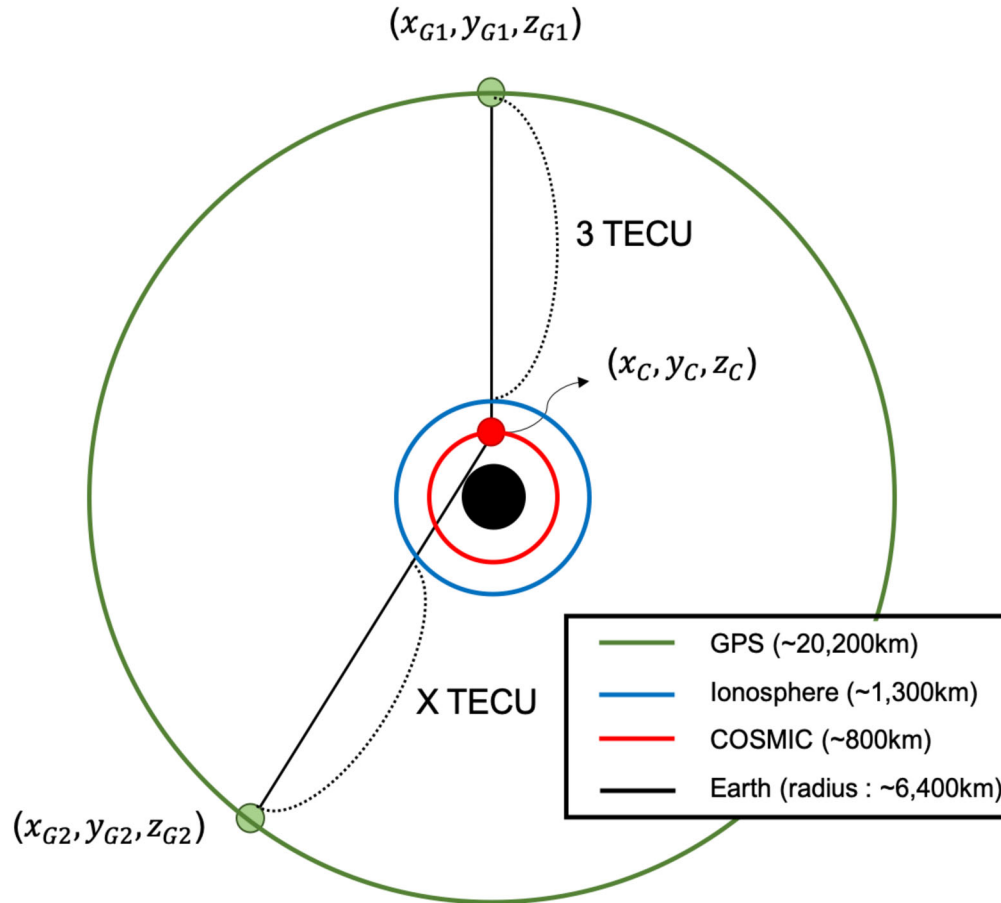


Fig. 2. The Schematic diagram for estimating plasmaspheric TEC from the COSMIC measured TEC.

the COSMIC-STECh data and COSMIC-NmF2 data included are 10,829 and 380, respectively, during the test periods of March, June, September, and December in 2015 (16 days), as listed in Table 1. The criterion for selecting the test period days for each month is

to include both geomagnetic quiet and disturbed conditions. Fig. 1 displays the geomagnetic conditions (Kp, Dst index) for the test periods. The total number of data points for GPS-STECH is 75,118 for the entire periods.

Fig. 2 is a schematic diagram showing the positions of GPS and COSMIC satellites. The plasmaspheric TEC contributes the STECH values measured by COSMIC satellites and must be removed, as did the ground-based GPS-STECH. The pathlength of the plasmasphere is calculated based on the location information of the COSMIC (x_c, y_c, z_c) and GPS (x_g, y_g, z_g) satellites. In Fig. 2 the location G1 of the GPS satellite is just overhead the COSMIC satellite, the TEC between the G1 and the top of the ionosphere (1,336 km) was adopted as a constant plasmaspheric vertical TEC of 3 TECU, that is the average vertical plasmaspheric TEC at the mid-latitude. For an arbitrary location of GPS satellite, marked as G2, the plasmaspheric contribution, X TECU, was computed by multiplying the pathlength ratio (slant pathlength to vertical pathlength as indicated in Fig. 2) to the adopted vertical

Table 1. Test periods and the numbers of GPS-STECH and COSMIC-STECH, and COSMIC-NmF2 data.

Month	Period	GPS STECH	COSMIC STECH	COSMIC NmF2
March	2015. 03. 15 (DOY 74) – 2015. 03. 18 (DOY 77)	20157	2390	78
June	2015. 06. 22 (DOY 173) – 2015. 06. 25 (DOY 176)	20152	3509	156
September	2015. 09. 07 (DOY 250) – 2015. 09. 10 (DOY 253)	16851	2825	101
December	2015. 12. 18 (DOY 352) – 2015. 12. 21 (DOY 355)	17958	2105	45
Total	16 days	75118	10829	380

plasmaspheric TEC of 3 TECU. As in the ground-based GPS-STECH, the COSMIC-STECH was calibrated by subtracting X TECU, that is

$$\text{Calibrated COSMIC-STE}C_i = \text{COSMIC-STE}C_i - X \text{TECU} \quad (2)$$

2.3 IDA4D

The IDA4D code is based on the 3D-var algorithm (Daley, 1991; Daley and Barker, 2000), which reconstructs the 3-D electron density of the ionosphere that varies with space and time by combining the background model and observation information (Bust et al., 2004). The IDA4D obtains the optimal solution by taking into account the time difference of the data set collected in the assimilation window that is defined by the user. In this paper, we only briefly describe the IDA4D algorithm. Readers refer to Mengist et al. (2019) and Bust et al. (2004) for a detailed description of the IDA4D algorithm.

The analysis state (electron density) is defined as the optimal solution that satisfies a minimum of the cost function,

$$J(\vec{x}) = 0.5[\vec{y} - \vec{H}\vec{x}]^T \vec{R}^{-1}[\vec{y} - \vec{H}\vec{x}] + 0.5[\vec{x}_f - \vec{x}]^T \vec{P}_f^{-1}[\vec{x}_f - \vec{x}] \quad (3)$$

where $\vec{y}$ is the observation (STEC, etc), $\vec{H}$ is the forward operator that relates the state to the observation, $\vec{x}$ is the electron density, and $\vec{x}_f$ is the forecast electron density; $\vec{R}$ and $\vec{P}_f$ are the error covariances of the observation and the forecast, respectively. According to the Gauss-Markov conjecture (Howe et al., 1998), $\vec{x}_f$ and $\vec{P}_f$ can be expressed as

$$\vec{x}_f(t_{n+1}) = e^{-\frac{\Delta t}{\tau}} [\vec{x}_a(t_n) - \vec{x}_b(t_n)] + \vec{x}_b(t_{n+1}) \quad (4)$$

$$\vec{P}_f(t_{n+1}) = e^{-\frac{2\Delta t}{\tau}} [\vec{P}_a(t_n) - \vec{P}_b(t_n)] + \vec{P}_b(t_n) \quad (5)$$

where t_{n+1} is the present time step, t_n is the previous time step, $\vec{x}_b$ and $\vec{P}_b$ are the background electron density from the IRI-2016 model and the background error covariance, respectively, and τ is the correlation time. In this study, we set τ to 3 hours for the geomagnetic quiet condition and to 1 hour for the geomagnetic storm condition (e.g., Bust et al., 2001; Gail et al., 1993). The analysis state and its error covariance can be obtained as follows.

$$\vec{x}_a = \vec{x}_f + \vec{P}_f \vec{H}^T [\vec{H} \vec{P}_f \vec{H}^T + \vec{R}]^{-1} (\vec{y} - \vec{H} \vec{x}_f) \quad (6)$$

$$\vec{P}_a = \vec{P}_f + \vec{P}_f \vec{H}^T [\vec{H} \vec{P}_f \vec{H}^T + \vec{R}]^{-1} \vec{H} \vec{P}_f \quad (7)$$

Eq. (6) indicates that the forecast electron density, $\hat{x}_f$ is corrected by the observed information, y , thereby assimilating the data into the background model that was used in Eq. (4).

Table 2. Location of the ionosonde sites.

Station name	Country	Geographic		Geomagnetic	
I-Cheon	S. Korea	37.14°N	127.54°E	27.80°N	161.86°W
Jeju	S. Korea	33.43°N	126.30°E	24.04°N	162.72°W
Okinawa	Japan	26.33°N	127.80°E	17.06°N	160.88°W
Kokubunji	Japan	35.70°N	139.50°E	27.17°N	150.89°W
Wakkanai	Japan	45.40°N	141.70°E	36.99°N	150.17°W

2.4 Ionosondes for Validation

To validate the results of the IDA4D assimilation, we use the peak frequency of the F2 layer measured by ionosondes. An ionosonde transmits radio waves and records the reflected radio waves by the ionosphere as an ionogram. By reading off the highest frequency of the reflected waves (foF2) in the ionogram, an ionosonde can estimate the peak electron density of the ionospheric F2 layer that is the main feature of the ionosphere. We utilized foF2 data measured by five ionosonde stations in the vicinity of the Korea Peninsula listed in Table 2. The foF2 data were obtained from ftp.ngdc.noaa.gov. The ionosondes produce ionograms every 15 min and routinely scaled by an auto-scaling software, called the Automatic Real-Time Ionogram Scaler with True Height (ARTIST) program developed at the University of Massachusetts Lowell (Galkin et al., 2008). The ARTIST program provides confidence levels from 11 (highest) to 55 (lowest) for the measurement quality of the ionogram (Galkin et al., 2013). We use the auto-scaled foF2 data with confidence levels of 11 to 33.

3. Results and Discussion

We evaluate the performance of the IDA4D in the four combinatorial cases of multiple data types during the test periods in March, June, September, and December in 2015. All the test periods include both quiet ($K_p < 4$) and storm ($K_p > 6$) conditions, as shown in Fig. 1. The assimilation was performed on four cases of data combinations: (Case 1) GPS-STECS only; (Case 2) GPS-STECS and NmF2's from COSMIC; (Case 3)

GPS-STECS and COSMIC-STECS; and (Case 4) GPS-STECS, COSMIC-STECS and NmF2's from COSMIC. The assimilation window of 15 minutes and spatial resolution $1^\circ \times 2^\circ$ in latitude and longitude were used in the vicinity of the Korea Peninsula (covering 20° - 60° N and 110° - 160° E). The vertical resolutions were 10 km, 25 km, and 52.4 km for the altitude ranges of 80 - 150 km, 150 - 500 km, and 500 - 1,336 km, respectively.

Fig. 3 displays the comparison of IDA4D and IRI foF2 values with the ionosonde measured values at the five stations on 22-25th June, 2015. The foF2 values of observed and IRI are shown with black and red, respectively, and those of IDA4D Case 1, Case 2, Case 3 and Case 4 are presented with blue, green, orange and purple, respectively. As shown in Fig. 1. (b) and Fig. 3, during the quiet part of June 22, foF2's of both IRI and IDA4D are relatively close to ionosonde foF2's, but for the disturbed condition, the IDA4D values show better agreement with the ionosonde ones than those of the IRI model. We have checked the foF2 values computed from the IRI model with storm option "on", but found no appreciable difference from those with storm option "off". The IRI model performance during geomagnetic storms has been known to be not as good as for quiet days (Fuller-Rowell et al., 2000; Araujo-Pradere et al., 2002; Kumar and Kumar 2019; Panda et al., 2020; Pignalberi et al., 2016; Timoçin et al., 2018). For Wakkanai and Kokubunji, there are some occasions when the IDA4D foF2 values are significantly different from the ionosonde values. We looked into the ingested data set (mostly ground-based GPS STEC) on June 22, and found quite a few STEC rays passing around Wakkanai station. These STEC data lead to the results of IDA4D models, which deviate from the ionosonde foF2 for most of the day. We note that the Wakkanai ionosonde foF2 values show particularly erratic variation (large fluctuations) on this day. This erratic variation should be in very local nature because the ingested STEC data in nearby area do not show this kind of variation. The current version

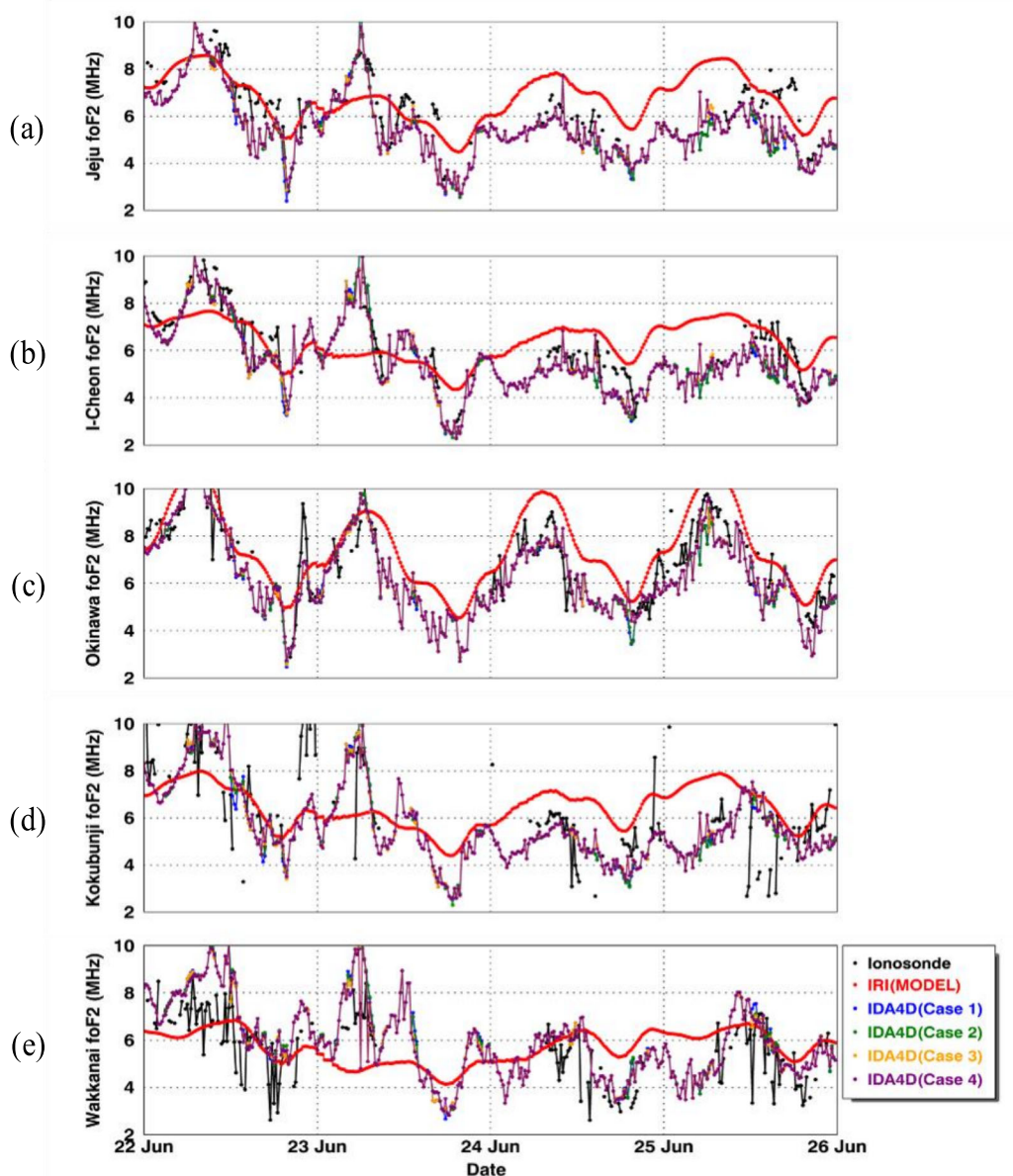


Fig. 3. The foF2 variation at Jeju (a), I-Cheon (b), Okinawa (c), Kokubunji (d), and Wakkanai (e) on 22-25th June 2015. The foF2 values of observed and IRI are shown with black and red, respectively, and those of IDA4D Case 1, Case 2, Case 3 and Case 4 are presented with blue, green, orange and purple, respectively.

of the IDA4D models cannot reflect small scale variation, due to smoothing over the correlation lengths of 5° (latitude) and 10° (longitude) that are implemented in the algorithm (Bust et al, 2004).

Fig. 4 presents the scatter plots of model foF2's vs ionosonde measured foF2's for the five stations over the entire test periods of 2015. The red, blue, green, orange, purple circles indicate the IRI model, IDA4D results for Case 1, 2, 3, and 4, respectively. Root mean square error (RMSE) and correlation coefficient (CC) between the model and measured

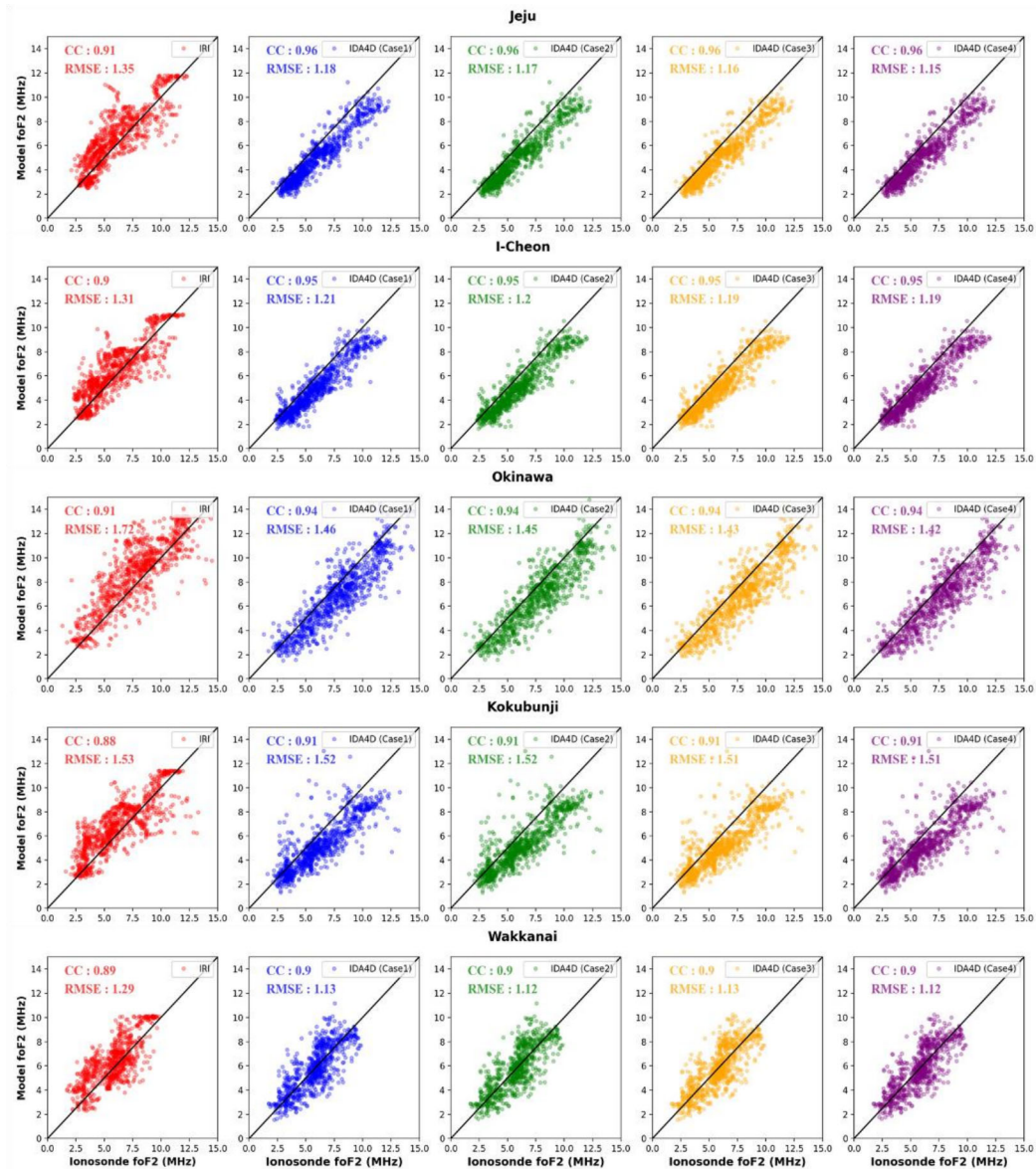


Fig. 4. Scatter plots of IDA4D (case1: blue, case 2: green, case 3: orange, case 4: purple), IRI (red) vs. ionosonde foF2 values at the five stations. RMSE and CC represent root mean square error and correlation coefficient, respectively.

values are provided in Table 3. The IDA4D RMSE values for all four cases are smaller than those of IRI, and the IDA4D CC values are closer to the unity than the corresponding IRI values for all stations. Overall, the IDA4D assimilation with GPS-STECH data only (Case 1) improves foF2 estimation by 9% in RMSE and by 3.2% in CC from the background model (IRI-2016). However, the IDA4D foF2 (NmF2) values in Fig. 4 are slightly underestimated at most ionosonde stations. The reason for this may be related to the general overestimation of IRI foF2 values that can be seen in the first column of Fig. 4. Because our assimilation

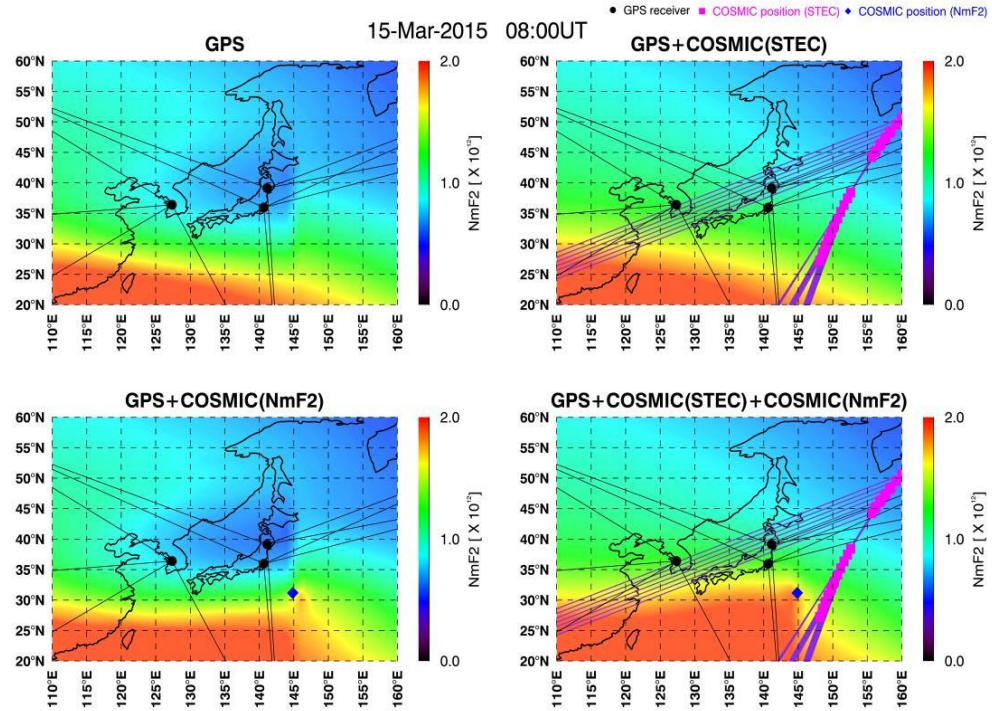


Fig. 5. The maps of IDA4D NmF2 for four assimilation cases at 08:00UT on March 15th, 2015. The black line and dot represent the GPS-STECh ray and GPS receiver, respectively. The violet line and magenta square symbol represent the COSMIC-STECh ray and the position of COSMIC satellite, respectively, for every four datapoints. The blue diamond symbol indicates the location of COSMIC-NmF2 value included in the assimilation.

uses the IRI profile as a base model, the assimilation algorithm seems to match the ingested STECh data by reducing the overestimated IRI foF2 values excessively, leading to the underestimation of foF2.

Compared to Case 1, foF2's for Case 2 and Case 3 are a bit closer to ionosonde foF2's. Because only small numbers of COSMIC-STECh and NmF2 data points (10,829 and 380), relative to that of GPS STECh data points (75,118), were ingested in the assimilation, the results of Case 2 and Case 3 are not much different from those of Case 1. However, despite the small number of COSMIC-NmF2 data being ingested, its distribution within the area near the Korean Peninsula has positive influence for the assimilation results. As Case 4 ingested all the data types into the assimilation model, the RMSE values for Case 4 are better than for all the other cases: on average, RMSE values are improved by ~1.5% from other cases. Table 3 summarizes RMSEs and CCs for the four cases of IDA4D and for the IRI model at the five ionosonde stations.

Mengist et al. (2019) reported the assimilation results for a 4-day period in the same region as ours. Their assimilation utilized GPS STECh's, ionosonde NmF2's and COSMIC NmF2's, and the performance was evaluated by comparing with ionosonde foF2's. Naturally,

the performance of their assimilation with ionosonde NmF2's (their Case 2, 3, 4) was significantly better than that with only GPS STEC's (their Case 1). Our assimilation (all cases) does not include ionosonde NmF2's, but was

Table 3. The performance parameters of data assimilations.

	IRI model		Case 1		Case 2		Case 3		Case 4	
	RMSE (MHz)	CC	RMSE (MHz)	CC	RMSE (MHz)	CC	RMSE (MHz)	CC	RMSE (MHz)	CC
I-Cheon	1.31	0.90	1.21	0.95	1.20	0.95	1.19	0.95	1.19	0.95
Jeju	1.35	0.91	1.18	0.96	1.17	0.96	1.16	0.96	1.15	0.96
Okinawa	1.72	0.91	1.46	0.94	1.45	0.94	1.43	0.94	1.42	0.94
Kokubunji	1.53	0.88	1.52	0.91	1.52	0.91	1.51	0.91	1.51	0.91
Wakkanai	1.29	0.89	1.13	0.90	1.12	0.90	1.13	0.90	1.12	0.90
Overall	1.44	0.90	1.30	0.93	1.29	0.93	1.28	0.93	1.28	0.93

Note. Assimilation Case1: GPS-STE_C, Case 2: GPS-STE_C+COSMIC-NmF₂, Case 3: GPS-STE_C + COSMIC-STE_C, Case 4: GPS-STE_C+ COSMIC-STE_C + COSMIC-NmF₂

compared with ionosonde foF₂'s as "ground truth". The performance of our assimilation in terms of foF₂ RMSE (overall RMSE = 1.30 ~1.28 MHz in Table 3) is indeed very close to that of Mengist et al's Case 1 (1.31 MHz). The fact that our assimilation included four test periods of 16 days and still shows just about equal performance to Mengist et al's Case 1 indicates the robustness of the assimilation algorithm. The effect of COSMIC STE_C's and COSMIC NmF₂'s in our assimilation is less impacting to improve the performance than the effect of ionosonde NmF₂'s in the Mengist et al's assimilation.

To elucidate the effect of each data type on the assimilation, we plotted the NmF₂ map within the range of the assimilation model in Fig. 5. Within the assimilation time window (15min), GPS-STE_C rays and GPS receivers are indicated with the black lines and dot, respectively, and the COSMIC-STE_C rays and position of COSMIC satellite are marked with the violet lines and magenta square symbols, respectively. In addition, the blue diamond symbol indicates the location for the COSMIC-NmF₂ that is included in the assimilation. The NmF₂ maps in Fig. 5 were calculated with data obtained between 07:45 – 08:00 UT on

March 15, 2015. When using only GPS-STECH data (Case 1), the map (upper left) displays that the NmF2 values are low in the sea area between Korea and Japan. When COSMIC-STECH data are added (Case 2), the NmF2 values in the map (upper right) are smoothly distributed over the most of the regions. The COSMIC-STECH rays fill the sea area between Korea and Japan, leading to the smooth NmF2 distribution. The map of Case 3 (lower left) differs from that of Case 1 only near the location marked with a blue diamond, where a COSMIC-NmF2 value was added to the assimilation. Finally, when both COSMIC-STECH and COSMIC-NmF2 values are added (Case 4), the map (lower right) is modified from the map of Case 2 by increasing NmF2 in the area around $\sim 30^{\circ}\text{N}$, where the COSMIC NmF2 was added. The maps for Case 3 and 4 have unrealistic sharp variation near the COSMIC NmF2 point, although the IDA4D algorithm smoothed NmF2 values with preset correlation lengths of 5° and 10° in latitude and longitude, respectively. It is noteworthy that both GPS and COSMIC- STECH data play an important role in filling large areas. Particularly, the COSMIC-STECH data contribute significantly to the assimilation in the remote area where the ground-based GPS receivers could not obtain data. On the other hand, COSMIC-NmF2 data should be used with caution because they are affecting in a very small area (almost a single grid), unless they are distributed with a significant number.

As listed in Table 1 the number of GPS STECH rays is much greater than that of COSMIC STECH and that of COSMIC-NmF2 point. For all days, the number of COSMIC-STECH rays is only $\sim 14.4\%$ of GPS-STECH rays, and the number of COSMIC-NmF2 points is even smaller. This means that GPS-STECH data are dominant in the assimilation, covering wider areas and times. Furthermore, since the number of COSMIC satellites is small, sometimes no COSMIC data was available within 15 minutes of the assimilation window. In this situation, data assimilation is performed only with GPS-STECH data. Due to this dominance, Case 2, 3, and 4 do not show much improvement in RMSE and CC from Case 1. Nevertheless, ingesting COSMIC data types into the assimilation is still beneficial because the additional COSMIC data cover the remote area where GPS data are lacking.

Fig. 6 shows the electron density profiles derived from COSMIC and I-Cheon ionosonde during the geomagnetic storm starting at 18:45UT on March 18th, 2015. The calculated profiles of the IRI

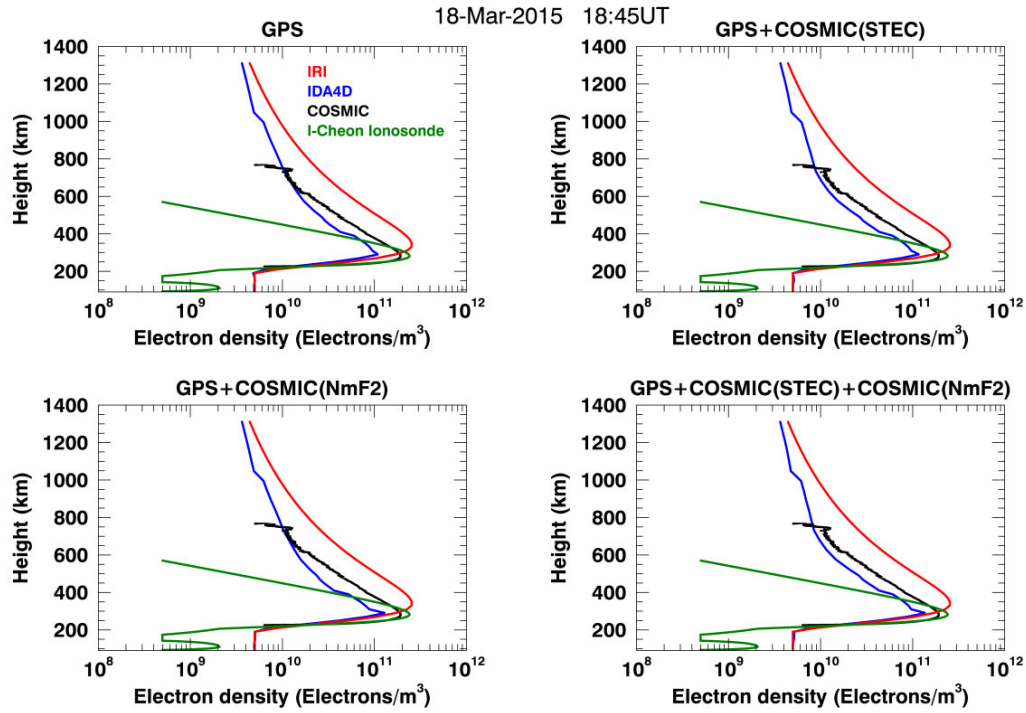


Fig. 6. The electron density profiles of IRI (red), IDA4D (blue), COSMIC (black) and ionosonde (green) at 18:45UT on March 18, 2015.

model and the IDA4D assimilations are also over-plotted. The IRI topside electron density is much larger than that of COSMIC, implying that the IRI model overestimates the electron densities of the F2 peak and above (Cherniak et al., 2019, Hong et al., 2017). When COSMIC-NmF2 was ingested (Case 2, 4), the electron density near the peak height of F2 layer (hmF2) is modified significantly. Electron densities at the topside (above the F2 peak) are more influenced in Case 3 than in Case 2. Specifically, the electron densities at the topside (from F2 peak to 1336 km) in Case 2 and Case 3 differ from the topside electron density from COSMIC by 0.51×10^{11} and 0.46×10^{11} electron/m³ in terms of RMSE, respectively. Therefore, it can be seen that when COSMIC-STEC was ingested (Case 3), the electron density at the topside was marginally improved.

In order to evaluate the assimilation effect quantitatively, we integrated the electron density profiles from 80 km (the minimum altitude we set) to the hmF2, called bottom side TEC, and from the hmF2 to the top of the ionosphere (1,336 km), called the topside TEC. For the ionosonde data, the electron density of the bottom side is reliable because the ionosonde directly measures the electron density below the F2 peak, while the electron density of the topside is modeled by ARTIST, the built-in software of the ionosonde. On the other hand, for COSMIC satellite data, the topside electron density is rather reliable while the bottom side electron density is calculated using Abel transformation through several

assumption and approximations, which may inherently lead to inaccurate densities at low altitudes (Lei et al., 2007; Schreiner et al., 1999). We found 23 RO electron density profiles that matched

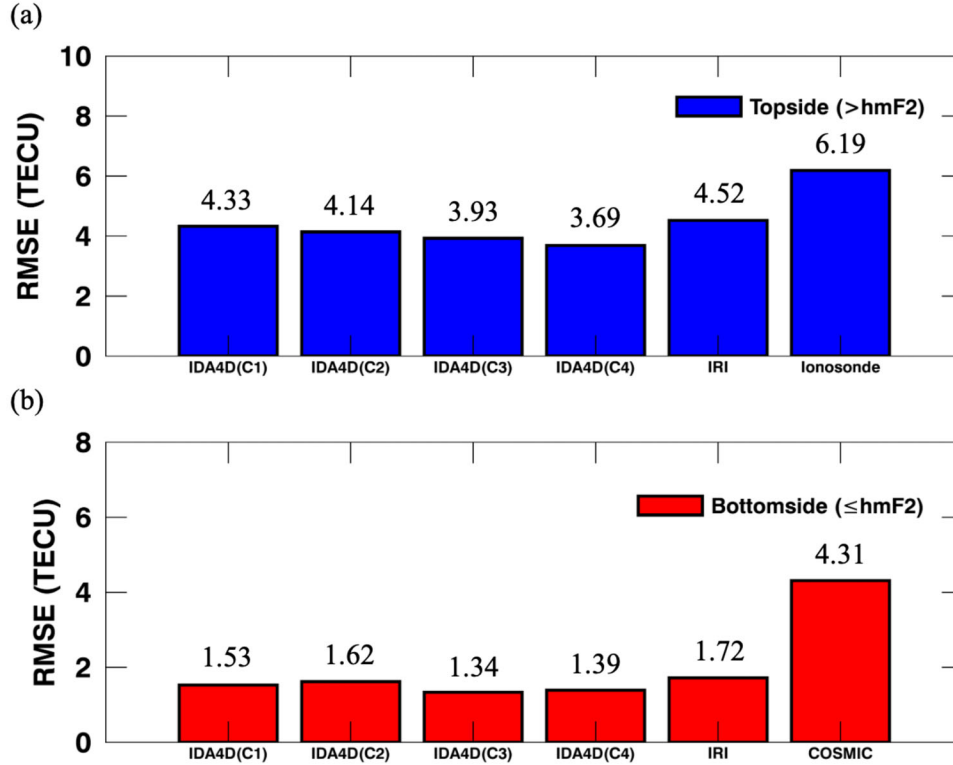


Fig. 7. The bar graph of RMSE from the topside COSMIC TEC's (a) for 23 events that coincided the COSMIC RO and the five ionosonde stations during the 16-day test period. (b) The same for RMSE from the bottom side ionosonde TEC's.

with the locations of the five ionosonde stations during the total 16-day test periods. Fig. 7 (a) presents the RMSE from the topside TEC's of COSMIC that are regarded as the reference and Fig. 7 (b) does the same with respect to the ionosonde bottom-side TEC's. It is evident from Fig. 7 that the IDA4D TEC's for all cases are closer to those of the reference than those of IRI. The closeness to the reference TEC values seems increasing as more data were ingested (case 1 → case 4). It is also worth noting that the topside TEC of ionosonde and the bottom-side TEC of COSMIC are more variable with respect to the reference TEC values than those of IRI and all model cases. This confirms that the ionosonde topside profiles and COSMIC bottom-side profiles are uncertain due to the model assumption in ARTIST and the Abel transformation, respectively.

4. Summary and Conclusions

In this study we evaluate the performance of the data assimilation model (IDA4D) by ingesting multi-type data (GPS STEC, COSMIC STEC, COSMIC NmF2) into the empirical model (IRI-2016) around the Korean Peninsula. The evaluation was carried out by comparing the IDA4D results with the measured peak frequency of the F2 layer (foF2) by five ionosondes (Jeju, I-Cheon, Okinawa, Wakkanai, Kokubunji) during the test periods of March, June, September and December in 2015. The comparison shows that the IDA4D assimilation performs much better than the IRI model. On average, RMSE between the IDA4D and ionosonde foF2 decreased by ~9%, and CC increased by ~3.2% from those of the IRI model. The performance of the IDA4D assimilation was best when all the three-type data were ingested (Case 4). Depending on the presence or absence of COSMIC-STECh rays and of COSMIC-NmF2 points, the data assimilation results were greatly affected in the area covered by these rays and data points. However, the number of COSMIC data is relatively small compared to that of GPS data in the vicinity of the Korean Peninsula. Thus, it is recommended that COSMIC STECh and COSMIC NmF2 data should be included as many as possible to cover the area where the ground-based GPS STECh data were lacking. In addition, the IDA4D yields better electron density profiles and TEC values than the IRI model, when compared with observed values. Therefore, we conclude that the IDA4D model can be used as a reliable nowcast model around the Korean Peninsula if the three-type data are ingested sufficiently. In the future, we will evaluate the performance of the IDA4D by ingesting other types of data, such as Incoherent Scatter Radar (ISR) or HF radar.

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V. Comparative study of low, middle and high latitude ionospheric irregularities over northern hemisphere along 120 – 130° longitude sector

1. Introduction

At altitudes above ~80 km, the molecular and atomic constituents of the Earth's atmosphere are ionized by solar ultraviolet radiation and energetic particles of solar and magnetospheric origin. The resulting plasma referred to as the ionosphere may have electron density variations, termed as ionospheric irregularities. The small scale size (~ 400 m) ionospheric irregularities may cause L-band radio wave signal scintillations, inducing severe signal degradation and even loss of lock (Beniguel and Adam, 2007; Blaunstein and Plohotniuc, 2008; and Hargreaves, 1992). Because of such effects, several studies have been devoted to characterize the ionospheric irregularities.

Examples of studies that have revealed latitudinal variation of ionospheric irregularities based on the whole globe as study area include, Tsybulya and Jakowski (2005), Su et al. (2006), and Zakharenkova et al. (2016). The global distribution of the topside (above 600 km) occurrence of ionospheric irregularities was investigated by Su et al. (2006) using the Republic of China Satellite (ROCSAT) data. They grouped the global occurrence distribution of the ionospheric irregularities into the equatorial and middle/sub-auroral latitude regions. Su et al. (2006) reported that the occurrence of equatorial irregularities increased with increase in solar flux level and geomagnetic disturbance. Furthermore, the equatorial irregularity peaked before local time midnight while the mid-latitude ionospheric irregularities mostly occurred during low solar activity period and showed less dependency on geomagnetic disturbance. Moreover, the mid-latitude irregularity occurrence was high after local time midnight. Su et al. (2006) concluded that such opposite characteristics in the occurrence pattern of ionospheric irregularities between equatorial and mid-latitude suggest that different instability generation mechanisms operate at the two latitude regions. Zakharenkova et al. (2016) presented the ionospheric irregularities occurrence detected by global positioning system (GPS) receiver and Langmuir probe onboard the Swarm satellites. They observed highest occurrence rates of the post-sunset equatorial ionospheric irregularities in September and March equinoxes and the lowest values in June solstice. Tsybulya and Jakowski (2005) used the radio occultation measurements made by the Challenging Mini-Payload (CHAMP) satellite to study ionospheric irregularities in the F layer and below under different geophysical conditions. The ionospheric irregularities with scale sizes of 20 – 100 km and 100 – 250 km dominated at high and low latitude regions, respectively. Moreover, the high latitude irregularities occurred mostly at night time when the ionization level was low. Blaunstein and Plohotniuc (2008) mentioned that many external

(e.g., high-energy particle precipitation, solar wind, and magnetosphere–ionosphere coupling) and internal factors such as convection of currents due to coupling between high conductive E- and F-regions may be responsible for formation of high latitude F-region irregularities. The plasma irregularities occurring in the high-latitude ionospheric F-region can be classified as large-scale (dimension $\sim 10 - 100$ km), moderate-scale (dimensions > 1 km), and small-scale (dimensions in hundreds of meters) (Blaunstein and Plohotniuc, 2008). Mechanisms such as the gradient drift and Kelvin-Helmholtz instabilities can cause a large-scale irregularity to break up at the edges, thereby generating smaller ones (Hargreaves, 1992). Generally, large-scale irregularities may progressively cascade to smaller ones with the passage of time.

In addition to the studies based on global study area, there are also studies that have considered regional study areas (e.g., Cervera and Thomas, 2006; Venkatesh et al. 2015; Zhao et al., 2021). The day-to-day variations in the occurrence of GPS L-band scintillations from equator to the equatorial ionization anomaly (EIA) crest location over the Indian region was described in a study done by Venkatesh et al. (2015). They inferred from the observations that the level of ambient ionization around noon-time, and a fast decay of the ionization during afternoon hours followed by rapid increase at the height of the F-layer contributes significantly to the occurrence of scintillations. Furthermore, their study indicated that the S4 index at L-band frequencies increases with an increase in latitude, maximizing around the crest of the equatorial ionization anomaly during the post-sunset hours. Venkatesh et al. (2015) concluded that the increased S4 index resulted into increased loss of lock events experienced by the GPS receivers around the EIA crest region. Over South-East Asian longitude sector, the study done by Cervera and Thomas, (2006) noted that the irregularity activity at the northern crest of EIA persists longer into the night during September equinox. This was suggested to be caused by the neutral winds that generate eastward electric fields asymmetric about the geomagnetic equator. Cervera and Thomas, (2006) also observed that during March equinox, the irregularity activity at the northern crest of EIA ends 1 hour earlier compared to that in September equinox. This seasonal difference in irregularity occurrence was attributed to either seasonal variation in the background ionosphere or in the seeding mechanism. Zhao et al. (2021) presented a comparative study of long-term occurrences of Equatorial Plasma Bubbles (EPB) kilometer-scale irregularities over equatorial and low latitudes sectors of Asian (about 120°E) and American (about 60°W) longitude sectors. Their results showed that (1) post-sunset EPB irregularities over the Asian sector were positively correlated with solar activity,

(2) geomagnetic disturbance tends to inhibit the generation of EPB irregularities during post-sunset but enhance their generation during post-midnight, and (3) the latitudinal distribution of EPB irregularities exhibited a double peak structure centered within dip latitude $\pm 10^{\circ}$ and latitudinal limit below $\pm 25^{\circ}$ at solar maximum. Li et al. (2021) stated that the generation of EPB depends on, (i) the F-layer bottom side plasma density wave structure

which seeds the Rayleigh Taylor (R–T) instability, and (ii) the driving forces (background electric field and neutral wind) which affect the F-layer height and field-line integrated conductivity, thus controlling the instability growth rate.

Unlike the global studies which may smear out details of features, regional studies may reveal more specific details of features over a particular region. It appears that no study has been done to reveal the approximate latitudinal boundaries of the ionospheric irregularity regions over the northern hemisphere along the 120 – 130° E longitude sector. Since it may be difficult to exhaustively describe the characteristics of ionospheric irregularities during both geomagnetically disturbed and quiet time in a single paper, this study investigated the occurrence of ionospheric irregularities over this region during quiet geomagnetic conditions. This study aimed at revealing the extent to which high- and low-latitude irregularities expand to middle latitude regions. Such investigations are usually important for planning development of empirical models. In section 2, the data sources and methods of analysis are presented. The results and discussions are presented in section 3 while section 4 presents the conclusions of the study.

2. Data sources and methods of analysis

This study used GPS signal phase observations to derive total electron content (TEC) which were in turn used to compute the rate of change of TEC (ROT) to represent ionospheric irregularities. The first application of GPS signal phase data fluctuations used to understand dynamic ionospheric morphologies was demonstrated by Aarons et al. (1996). Since ionospheric irregularities mostly occur during high solar activity periods (Nishioka et al., 2008), we analyzed ROT (representative of ionospheric irregularities) data during geomagnetically quiet days of the year 2014. This is the year with the highest yearly average solar flux level (145.82 sfu) during the period when Swarm satellites have operated thus far. Following previous studies (e.g., Matamba and Habarulema, 2018 and Mungufeni et al., 2019b), the geomagnetically quiet days were identified when all 8 values of Kp within the day were ≤ 3 . The Kp values were obtained from the world data center at Kyoto University, Japan (<http://swdcwww.kugi.kyoto-u.ac.jp/>). The ROT data analyzed in this study were obtained using both ground- and space-based GPS receivers. In sections 2.1 and 2.2, we provide brief information about ground- and space-based GPS derived ROT, respectively.

2.1 Ground-based GPS ROT

The locations of the ground-based GPS receivers used in this study are shown with red stars in Figure 1.

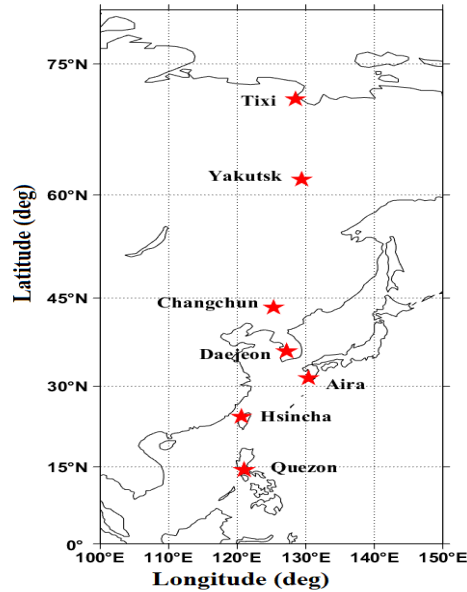


Figure 4: Name and location of GPS stations used in the present study

The receivers provide Receiver Independent Exchange data (RINEX) format files that can be accessed from the website of the University NAVSTAR consortium (UNAVCO) via the link, <ftp://data-out.unavco.org>. Table 1 provides more information about the locations of the ground-based GPS receivers used in this study. Based on classification of ionospheric regions as in Blaunstein and Plohotniuc, (2008), the magnetic latitudes shown in Table 1 include low (mag lat < 30°), middle (30 ≤ mag lat ≤ 55°), and high-latitude (mag lat > 55°) stations.

Table 1: GPS stations used in the study

Station Code	City	Geog Lat(°)	Geog Lon(°)	Geomag lat(°)
TIXI	Tixi	71.4	128.5	62.0
YAKT	Yakutsk	62.0	129.4	52.6
CHAN	Changchun	43.5	125.3	34.0
DAEJ	Daejeon	36.2	127.2	26.2
AIRA	Aira	31.5	130.4	22.3
TCMS	Hsincha	24.5	120.6	15.3
PIMO	Quezon	14.4	121.0	04.8

The RINEX files obtained from the stations listed in Table 1 were processed using GPS-TEC analysis software (Seemala and Valladares, 2011) to obtain STEC as a function of Universal Time (UT) and elevation angles of satellites tracked. It should be noted that the STEC

observed by a particular satellite has 30 seconds resolution. After removing satellite and receiver biases from STEC, the software maps it to VTEC at the ionospheric pierce points. The satellite biases are published by the University of Berne in Switzerland (<ftp://ftp.unibe.ch/aiub/CODE/>). The GPS-TEC analysis software estimates receiver bias for a specific receiver by trying several values and taking the one that gives the minimum summed standard deviation of observed VTEC during 03:00 - 06:00 LT. To minimize multipath effects, we only considered STEC values observed at elevation angles $>30^\circ$.

In this study, the STEC values associated with a particular visible GPS satellite were used to obtain corresponding ROT values. According to Pi et al. (1997), 1 TECU/min ROT value over high latitude would correspond to ionospheric irregularity with scale size of 30 km when the horizontal plasma drift velocity is ~ 1 km/s. On the other hand, high values of ROT over low and middle latitudes would correspond to ionospheric irregularities with scale sizes in the range of ~ 400 m – 2.5 km, depending on the plasma drift velocity. Aside from the usefulness of the ROT index to detect the occurrence of ionospheric irregularities and their scale sizes, it is not yet possible to ascertain the exact location of the irregularity region along the line joining the GPS receiver and a satellite. Next, we return to distribution of observations sites.

Since the latitudinal distribution of the ground-based GPS receivers over the study area (see Figure 1) is not uniform, their data was supplemented with that of the Swarm satellites. Consequently, the data analyzed in this study were those recorded during the year 2014 when Swarm satellites were operational.

2.2 Space-based GPS ROT

In this study, we used the Swarm satellites to obtain space-based GPS ROT. The Swarm constellation is composed of three identical satellites, namely; Alpha (A), Bravo (B), and Charlie (C). Detailed information about orbital characteristics of the Swarm satellites can be found in Zakharenkova et al. (2015). Each of the Swarm spacecraft carries a Precision Orbit Determination (POD) antenna. The GPS signal phase measurements done by this antenna can be used to estimate the TEC between Swarm and GPS satellites. The TEC data can be freely downloaded from the European Space Agency (ESA) website (<http://www.earth.esa.int/swarm>). Its resolution was 1 and 10 seconds after and before July 15, 2014, respectively.

As discussed in section 1, Zakharenkova et al. (2016) presented a comparison of the ionospheric irregularity occurrence detected by the GPS receiver and Langmuir probe onboard the Swarm satellites. They used the GPS receiver to derive TEC which in turn was used to compute the ROT Index (ROTI), while the Langmuir probe provided in situ electron density. Although Pi et al. (1997) defined ROTI to be computed at intervals of 5 minutes, Zakharenkova et al. (2016) computed this index at intervals of 15 seconds. Zakharenkova and Astafyeva (2015) stated that in situ electron density fluctuations obtained from Low Earth Orbit (LEO) satellites such as Swarm and the LEO-GPS ROT measurements detect ionospheric irregularities at different spatial scales and altitudes. They further

mentioned that whereas the LEO-GPS ROT technique relates to 2 dimensional (plane that contains line that joins the LEO and the GPS satellite) measurements, the in situ electron density fluctuation technique relates to 1 dimensional (at specific altitude and along the line of motion of the LEO satellite). Therefore, the LEO-GPS ROT technique can represent occurrence of ionospheric irregularities over much larger spatial area than in situ electron density fluctuations.

In line with these discussions, this study used ROT obtained from ground- and space-based measurements to study ionospheric irregularities. In order to clearly understand distribution of irregularities over the study area, full year data coverage was necessary. Particularly, we used both 1- and 10-seconds resolution Swarm TEC data measurements done during the year 2014. The 10 s resolution Swarm TEC data would render meaningless the computation of ROTI at intervals of ≤ 30 s (about 3 data points) to represent the severity of phase fluctuations. We think that computation of ROTI at intervals of > 30 s would still be meaningless considering the motion of the Swarm satellites. At a speed of ~ 7.5 km/s, the satellite would travel ~ 300 km ($\sim 2.5^\circ$ latitudinal separation) in 40 s. Therefore, the ROT values sampled at time intervals > 30 s to compute ROTI would represent ionospheric irregularities from different latitudinal regions. In order to get rid of this problem, we represented ionospheric irregularities using magnitudes of ROT computed when time difference between successive measurements were ≤ 10 sec.

It is important to mention that during ROT computation, we used TEC measurements of GPS satellites with elevation angle $> 50^\circ$ as observed by the Swarm satellite (e.g., Zakharenkova and Astafyeva, 2015 and Mungufeni et al., 2019a). It was important to apply a high elevation angle since LEO GPS receiver observations usually experience severe multipath effects (due to their solar panels) and relatively low signal-to-noise ratio especially at low elevation observations (Yue et al., 2011). Due to the applied high elevation mask angle, the ROT values were assumed at the location of the Swarm satellite. The spatial data binning (shown later in section 3.1) may minimize the disparity in position of a data point caused by this assumption. The TEC data from all three Swarm satellites A, B, and C were used in this study.

Table 2 presents the number of geomagnetically quiet days with available data from the GNSS stations together with number of days with Swarm satellite passes over the study area. The table also provides the number of days with Swarm satellite passes over the study area. The number of days with Swarm satellite passes in the months of the year 2014 is presented in columns 2 – 13 of Table 2. This allowed us to minimize the effect of seasons on occurrence of ionospheric irregularities and mainly observe the effect of latitudinal variation.

Table 2: Number of days with data during the study period

Data source	Year: 2014											
	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
Swarm (A)	24	16	27	17	23	25	30	17	18	16	15	9
Swarm (B)	22	15	27	17	23	23	30	16	16	14	13	9
Swarm (C)	23	16	27	17	23	25	30	17	18	15	15	9
AIRA	31	20	30	27	31	30	31	28	24	31	25	30
CHAN	31	20	30	27	31	30	30	29	28	31	28	30
DAEJ	30	20	30	27	29	28	28	29	27	29	28	30
PIMO	31	20	30	27	31	30	29	29	28	31	28	23
TCMS	31	17	30	22	31	30	30	29	24	30	27	25
TIXI	31	20	30	27	30	30	31	29	28	31	28	30
YAKT	31	20	30	27	30	30	31	29	28	31	28	30

3. Results and discussions

3.1 Normalization of Space-based GPS ROT

Pi et al. (1997) stated that ROT values mostly fluctuate around a low value (<5 TECU/min). It is shown in Figure 2 that several Swarm-derived ROT values are really high (>5 TECU/min). Panel (a) of Figure 2 presents the median ROT observed by all GPS satellites with elevation angle $>30^\circ$. The data presented in panel (a) were obtained from ESA web site (Wojciech et al., 2018) and the observations were made on quiet days of March, 2015. It needs to be pointed out that this period was preferred to March, 2014 because of higher TEC resolution (1 second) in March, 2015. Moreover, the observations were those close to the northern crest of EIA (geog lat: $12 - 32^\circ$ N; mag lat: $9 - 26^\circ$ N) and along the longitude sector considered in this study.

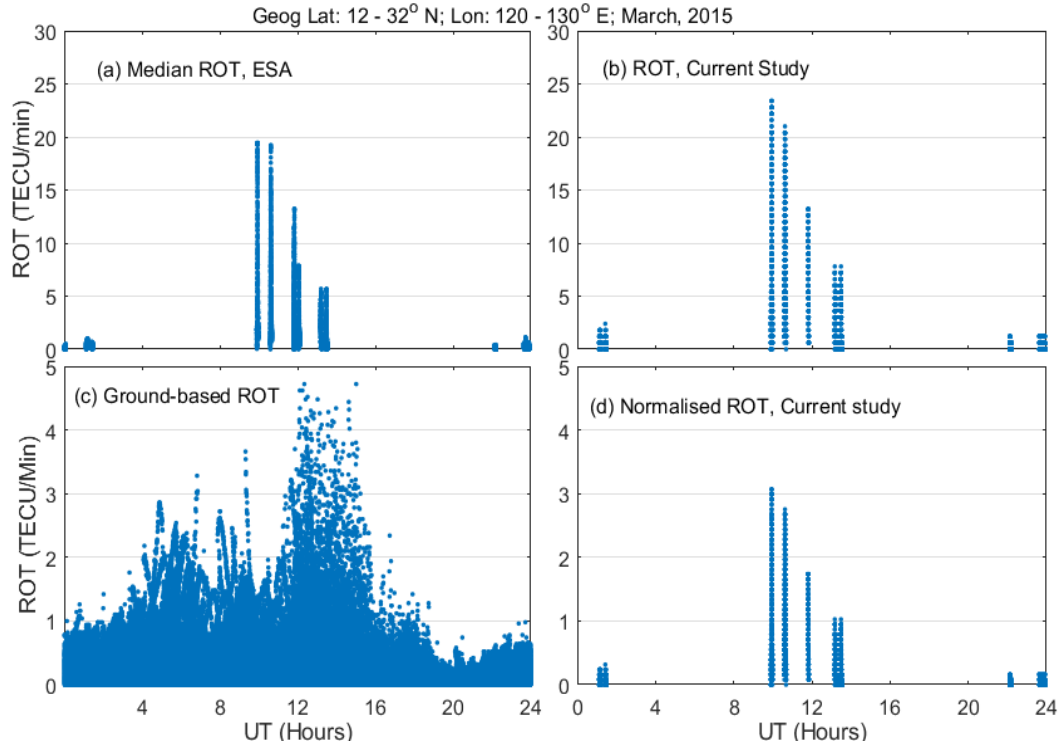


Figure 5: Panels (a) and (b) present Swarm-derived median ROT obtained from ESA website and Swarm-derived ROT in the current study, respectively. Panels (c) and (d) present the Ground-based ROT and Swarm normalized ROT, respectively. The data presented were observed over northern crest of EIA and along longitude sector 120 – 130° N during quiet geomagnetic days in March, 2015.

The ROT values we obtained using visible GPS satellites over the specified location and during the stated time period are presented in panel (b) of Figure 2. Indeed, several cases of high ROT values ($ROT > 5$ TECU/min) can be seen in Figure 2, panels (a) and (b). The high values of space-based GPS ROT (Figure 2a and 2b) compared to ground-based ROT (Figure 2c) could be due to the motion of the receiver. The high linear speed of the space-based GPS receiver (~ 7.5 kms⁻¹ for Swarm) might have resulted in an increased area over which ionospheric irregularities are observed, which in turn yields high ROT values observed by the receiver.

Based on the preceding discussions, we normalized the Swarm-derived ROT values by dividing the value at a specific time by the speed of the respective Swarm satellite at that time. It is demonstrated in Figure 2 that this normalization appears to minimize the effect of the motion of Swarm satellite on the ROT data. The speed of the Swarm satellite was computed based on the Cartesian coordinates of the satellite at two consecutive TEC data points and the time difference between the two measurements. It should be noted that the

Cartesian coordinates of the Swarm satellites are provided at the ESA website. After performing normalization, the ROT values appear reduced as shown in panel (d) of Figure 2. The magnitudes of the normalized ROT values appear comparable to that of ground-based ROT values and the variations of the two data sets also appear to be similar. This observation signifies that the speed of a moving GPS receiver might have a multiplying effect on the ROT data observed by the receiver. Regarding other techniques of data normalization, Zakharenkova et al. (2016) normalized electron density values that were obtained from the Swarm satellites by dividing the values by 10^6 el/cm^3 . They then used the normalized electron density values to compute the rate of change of electron density (ROD).

It is important to mention that the ground-based ROT in panel (c) of Figure 2 depicts the peak occurrence during 12:00 – 16:00 UT. This UT time interval is translated to LT by adding 9 hours ($\text{LT} = \text{UT} + 9 \text{ hours}$), yielding 21:00 – 01:00 LT. The night time occurrence of ionospheric irregularities over the low latitudes are usually explained by the irregularities in plasma bubbles which are generated by the post sunset enhancement of the zonal electric field through the Rayleigh-Taylor instability (Kelley, 1989).

In order to reveal the latitudinal spans of low, middle, and high latitude ionospheric irregularities, we used ROT values of the year 2014 when the high occurrence of ionospheric irregularities was expected. In subsection 3.2, we present latitudinal distribution of irregularities typically depicted by Swarm satellite-derived ROT under geomagnetically quiet conditions ($K_p \leq 3$) and in subsection 3.3, we present those depicted by independently binned ground-based and Swarm-satellite derived ROT.

3.2 Latitudinal distribution of irregularities typically depicted by Swarm satellite-derived ROT

Figure 3 shows typical Swarm satellite-derived ROT over the 120 - 130° E longitude sector. For clarity purposes, only the data over latitude range of 42 – 80° N are presented in upper row panels, while that over 0 – 40° N are in lower row panels. In Figure 3, panels in columns 1, 2, and 3 present the data observed during day (08:00 – 18:00 LT), before midnight (18:00 – 24:00), and after midnight (0:00 – 08:00 LT), respectively. The letters A, B, and C indicated in Figure 3 represent the Swarm satellites associated with the ROT values which are plotted. Moreover, the dates (format: Year/Month/Day of Month) of observing the Swarm satellites are indicated in brackets. Particularly, the data of equinox months (March and April) are presented since high occurrence of ionospheric irregularities are expected in that season.

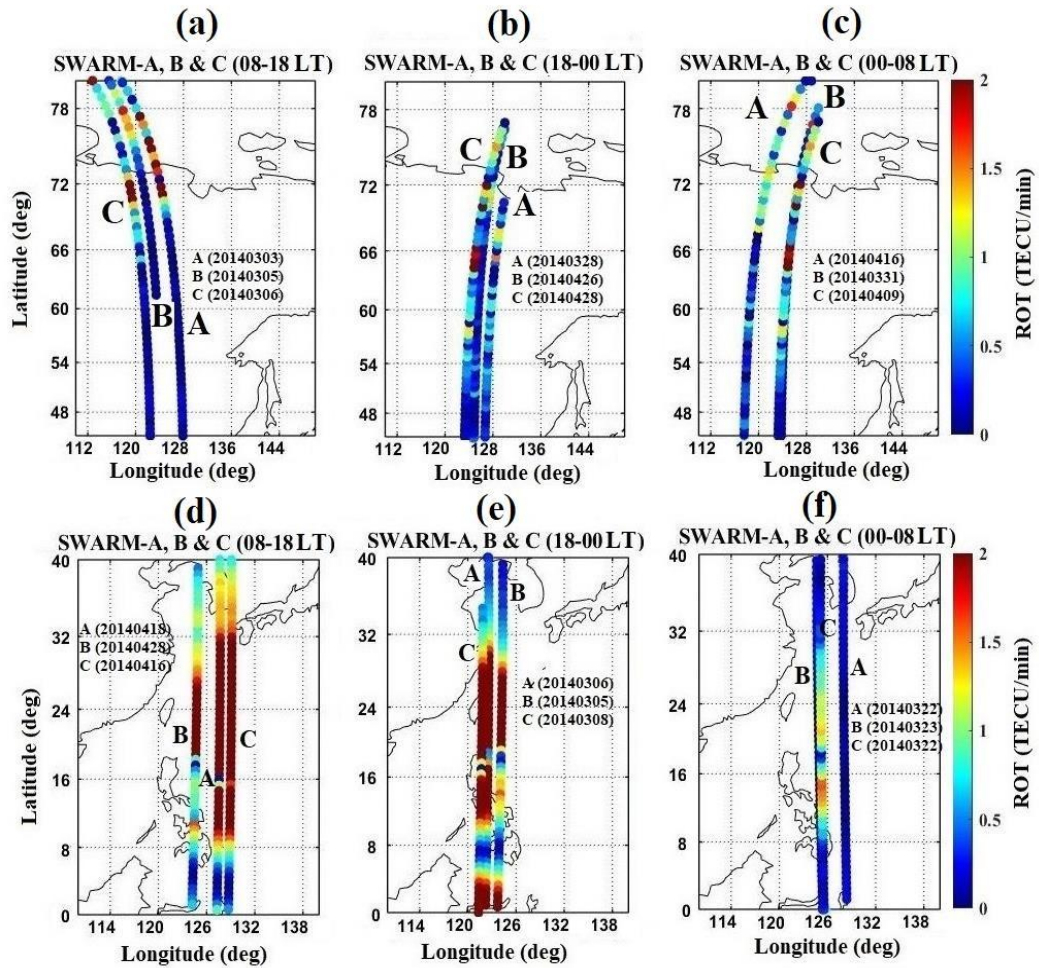


Figure 3: Variations of Swarm satellite-derived ROT over 120 – 130° E longitude sector. Panels (a), (b), and (c) present ROT values over 42 – 80° N latitude sector, while (d), (e), and (f) present those over 0 – 40° N. Panels in columns 1, 2, and 3 present the ROT values during day, before midnight and after midnight, respectively.

The distribution of Swarm satellite-derived ROT values in Figure 3 can be used to deduce the patterns of distribution of ionospheric irregularities over 120 – 130° E longitude sector. As expected, Figure 3 panels (d) and (e) reveal that ionospheric irregularities occur mostly over low-latitudes (0 – 40° N) during the day and before midnight. Although the severity of ionospheric irregularities over the Polar Regions (see upper row panels) appears to be less than that over the low latitude regions, ionospheric irregularities occur throughout the day over the former region. Figure 3, panel (e) clearly depicts the existence of high occurrence of irregularity over the southern Equatorial Ionization Anomaly (EIA) crest (< 4° N) and the northern EIA crest (12 – 32° N) before midnight. This result is similar to that reported by Venkatesh et al. (2015) over the Indian longitude sector, where they indicated that the S4

index at L-band frequencies increases with increase in latitude, maximizing around the crest of the equatorial ionization anomaly during the post-sunset hours.

Next, the approximate latitudinal boundaries of ionospheric irregularities were investigated further based on binned ROT values during the year 2014.

3.3 Latitudinal distribution of irregularities depicted by independently binned ground-based and Swarm-satellite derived ROT.

As mentioned earlier, this study used both ground-based and Swarm satellite-derived ROT values of the year 2014. The data were binned according to their geographical latitudes. The data were further binned according to the 12 months in a year and local time. The latitudinal bins had 2° resolution and the local time bins consisted of daytime (08:00 – 18:00 LT), nighttime before midnight (18:00 – 24:00), and nighttime after midnight (0:00 – 08:00 LT). Aarons et al. (1996) grouped the ROT values into 4 levels of (a) $ROT < 0.5$ TECU/min for low or no irregularities, (b) $0.5 \text{ TECU/min} \leq ROT < 1 \text{ TECU/min}$ for medium ionospheric irregularity occurrence, (c) $1 \text{ TECU/min} \leq ROT < 2 \text{ TECU/min}$ for high ionospheric irregularity occurrence, and (d) $ROT \geq 2 \text{ TECU/min}$ for extreme irregularity occurrence. Following these groupings, a local time bin in a particular latitudinal bin and month was represented in this study by one of the numbers in the range of 1 – 4 TECU/min. Normally it is undesirable to record in a particular bin even a single ROT value in group (d). One could assign number 4 to such a bin. However, since a single case of $ROT \geq 2 \text{ TECU/min}$ could be spurious data, we only assigned number 4 to a bin when 5 % of all data in the bin are in group (d). Similarly, if in a bin the highest ROT data is in range (c) and there is only 1 ROT value in this range, number 3 could be assigned to the bin. This is not done because the single case may be a spurious data. Therefore, when at least 5 % of all ROT data in the bin are in the range (c), the bin is assigned number 3. Following these ideas, number 2 is assigned to a bin when it is associated with group (b) and number 1 is assigned when it is associated with group (a). The various bins were assigned numbers 1 – 4 for easy graphical representation.

Figure 4 presents the ROT values (associated with numbers 1 – 4) as a function of month and geographic latitude. In the figure, panels in rows (a) and (b) present the ROT values that were determined using Swarm satellites and ground-based GPS receivers, respectively. The panels in columns (i) – (iii) present the ROT values that were determined during the day, before midnight and after midnight, respectively. The horizontal magenta arrows indicate the approximate lowest latitudes of high ionospheric irregularity occurrence. The white spaces indicate unavailability of data.

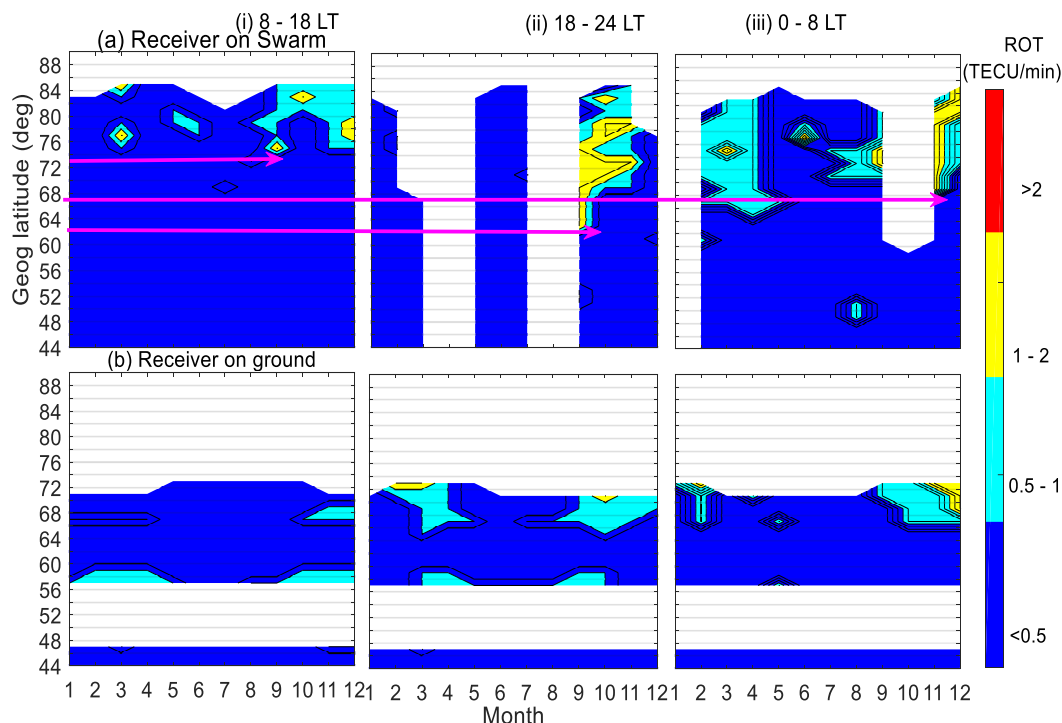


Figure 4: Variation of ROT as a function of latitude and month. Panels in rows (a) and (b) are ROT measured by GPS receiver on Swarm and ground, respectively. Panels in columns (i), (ii), and (iii) are for ROT measurement during day (08:00 – 18:00 LT), before midnight (18:00 – 24:00 LT), and after midnight (0:00 – 08:00 LT), respectively. Magenta arrows indicate approximate lowest latitude of high ionospheric irregularity occurrence.

For clarity purposes, the geographic latitude in Figure 4 was limited to include only mid-high latitude (geog lat: 44 – 90° N) regions. Figure 5 is similar to Figure 4 except, the geographic latitude was limited to include only low-mid latitude (geog lat: 0 – 44° N) regions. Another difference is that the magenta arrows in Figure 5 indicate the highest latitude of high ionospheric irregularity occurrence.

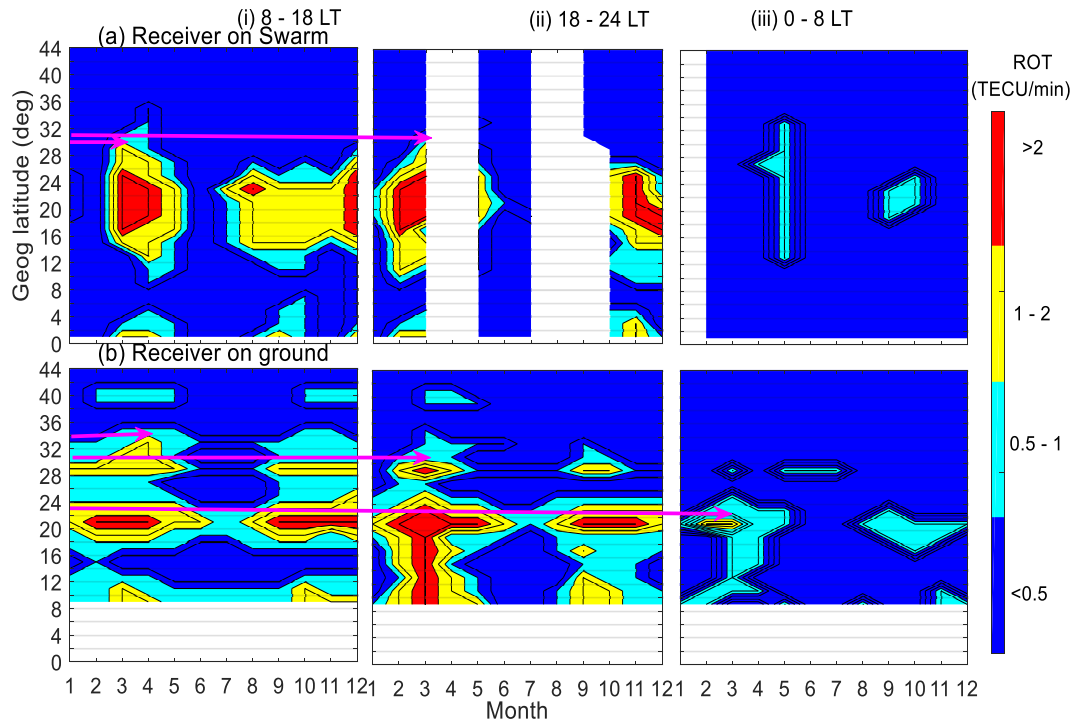


Figure 5: Similar to Figure 4, except for low-mid latitude (geog lat: 0 – 44° N) regions and the horizontal magenta lines indicate the highest latitude of high ionospheric irregularity occurrence.

Visual inspection of Figures 4 and 5 reveal that the variations of ROT observed using space-based GPS receiver are mostly consistent with that of the ground-based receiver. For example, both ground- and space-based observations show that (a) extreme (red colors) cases of ionospheric irregularities occur mostly over low latitude regions and low or moderate irregularities occur mostly over mid latitude regions, (b) high – extreme cases of ionospheric irregularities occur mainly over low latitudes during daytime and before midnight, while high cases of ionospheric irregularities occur mainly over high latitudes at night (before and after midnight).

The similarities in distribution of occurrence of ionospheric irregularities observed by ground- and space-based techniques is consistent with results of studies done by Olwendo et al. (2019), Cherniak and Zakharenkova (2016), and Zakharenkova and Astafyeva (2015). Similar to the explanations provided in these studies, the coincidental observations of moderate – high irregularities by ground- and space-based GPS receivers can be linked to the presence of ionospheric irregularities in the space between the latter receiver and the GPS satellites. The results of the current study support the idea that over locations which do

not have ground-based GPS receivers, space-based receivers can be a good option for studying ionospheric irregularities (Zakharenkova and Astafyeva, 2015).

Overall, the latitudinal distribution of high – extreme ionospheric irregularities displayed in Figures 4 and 5 show concentrations around geographic latitude ranges, (i) 1 – 4° N (geomag lat. -8.3 – -5.3° N), (ii) 9 – 34° N (geomag lat. 0.4 – 24.5° N), and (iii) 62.5 – 84° N (geomag lat. 52.9 – 74.4° N). Ionospheric irregularity occurrence concentration regions (i) and (ii) appear to be within southern and northern EIA crests, respectively, while region (iii) exists over the high latitude.

The panels in row (b) of Figure 5 depict two latitudinal peaks around the northern EIA crest region, while the panels in row (a) depict gradual changes of ROT around the same region. This observation where space-based measurements show gradual changes of ROT might be attributed to uniformly distributed measurement locations along the tracks of Swarm satellite. On the other hand, the ground-based observation points which are not uniformly distributed (see Figure 1) might have resulted into a non-gradual variation in ROT, appearing as two peaks.

Another difference in ROT distribution of ground- and space-based observation depicted in Figure 5 is the existence of low/no irregularities at around geographic latitude 8° N in row (a) panels. This observation may be associated to the location being almost coincident with the magnetic equator. Since ground-based observations depict high ROT values at this location (see panels in row (b) of Figure 5), the irregularities might exist at low altitudes such that space-based observations fail to detect them. At the magnetic equator, plasma is lifted to higher altitudes through the ExB drift. When diffusion of plasma along magnetic field lines take place due to gravity and pressure gradients, the irregular regions may be formed and transferred to the crests of EIA regions.

3.4 High latitude irregularities

Due to poor distribution of ground-based GPS receivers over the mid-high latitude regions (see Figure 1 and panels in row (b) of Figure 4), comparisons of latitudinal spans of ionospheric irregularities observed by the ground- and space-based GPS receivers may not be effective. Despite this limitation, it can be seen in Figure 4 panels in columns (i) and (ii) that unlike space-based observations which depict low occurrence of ionospheric irregularities over geographic latitude range of 56 – 60° N, the ground-based observation shows moderate irregularities. This might be due to irregularities that exist below the altitude of the Swarm satellite which can only be detected by ground-based observations. Another observation that can be made from Figure 4 is that panels in row (a) show that the lowest geographic latitude of high ionospheric irregularity occurrence were 74° N (geomag lat. 64.4° N), 62.5° N (geomag 52.9° N), and 68° N (geomag lat. 58.4° N) during the day, before

midnight and after midnight, respectively. These lower boundaries of the high latitude irregularity are slightly lower than those on the quiet day of March 16, 2015 that were reported by Cherniak and Zakharenkova, (2016). They found that during the day, the position of the irregularities derived from ground GPS measurements was around 75° corrected magnetic latitude (MLAT). They also reported intensification of irregularities within 65° – 70° MLAT in the midnight sector. They attributed the irregularities at 15 MLT (during the day) to the dayside cusp precipitation and those at midnight sector to magnetotail precipitation. The difference in the equator-ward boundary of irregularity regions in our study compared to that of Cherniak and Zakharenkova, (2016) could be due to the fact that our study relied on monthly data while the other study relied on 1 day data.

Another study on the high latitude ionospheric irregularity occurrence during low - moderate magnetic activity conditions reported that the lowest geomagnetic latitude (most equatorward extension) 57° N at which the irregularities were observed was attained before local midnight (Aarons, 1973). Moreover, the daytime boundary in the equator-ward direction of the ionospheric irregularities was at magnetic latitude 70° N. It should be noted that the results of Aarons, (1973) were based on HF and VHF observations over longitude sector $51 - 71^\circ$ W, while the present study relied on L-band observations over $120 - 130^\circ$ E. Therefore, a direct comparison between our results and that by Aarons (1973) cannot be done. Nevertheless, it is interesting to note that the results of Aarons, (1973) based on monitoring amplitude scintillations from a geostationary satellite at an altitude of ~ 1000 km and radio star observations are close to what we obtained using LEO-GPS receiver.

Although the exact location of irregularities illustrated by the ROT may not be known, the high latitude irregularities observed in this study may be associated with E and F-region plasma density irregularities. Blaunstein and Plohotniuc, (2008) stated that the high-latitude E-region plasma density irregularities are completely controlled by the ionospheric currents and plasma drifts. Since the high latitude magnetic field is close to vertical with respect to Earth's surface, the ambient electric field transverse to the magnetic field as well as the neutral wind (with the horizontal component exceeding its vertical component) may produce E-region field-aligned plasma irregularities (Blaunstein and Plohotniuc, 2008 and Hargreaves, 1992). It would be appropriate to present simultaneous observations of E region ionospheric irregularities and ROT variation. Unfortunately, this was not possible since we did not have access to data obtained from high latitude region where there is an ionosonde which is co-located with ground-based GPS receiver. However, later in section 3.6 we present in Figure 6 simultaneous observations of sporadic E and ROT variation over the mid-latitude region.

As mentioned in section 1, the small-scale irregularities produce scintillation phenomena in trans-ionospheric radio signals. The moderate to high ROT values observed in this study

might correspond to scintillation effects produced by small-scale irregularities. Hargreaves, (1992) stated that scintillation tends to be particularly severe around the auroral zone and the polar cap. Moreover, the high-latitude scintillation zone expands towards the equator in the night sector. The latitudinal and local time distributions of high latitude irregularities mentioned in this study are in line with these two statements.

3.5 Low latitude irregularities

Figure 5 reveals that the highest geographic latitude of high ionospheric irregularity occurrence depicted by the ground- and space-based GPS receivers are 34° N (geomag lat. 24.5° N) and 30° N (geomag lat. 20.5° N), respectively. These observations represent concentrations of ionospheric irregularities over the crests of EIA and are consistent with the previously discussed results of Venkatesh et al. (2015) and Zhao et al. (2021).

Another study that found high occurrence of irregularities over the crests is that of Valladares et al. (2004). They used a latitudinally distributed network of GPS receivers within the longitudinal sector of $70 - 80^{\circ}$ W. The results showed that the maximum magnetic latitudes where scintillations occur range from $5 - 23^{\circ}$. Valladares et al. (2004) noted that the locations of the GPS receivers existing up to magnetic latitude of about 23° N might have limited observations of scintillations extending further poleward. The lowest magnetic latitude ($\sim 8^{\circ}$) of observing high ionospheric irregularities in this study is greater than the 5° that was reported by Valladares et al. (2004). Such differences might be attributed to different observation periods which yield different intensities of ionospheric irregularities. Another reason could be longitudinal differences in occurrence of ionospheric irregularities (Yizengaw and Groves, 2018) arising from different positions of the magnetic equator over the various longitudinal sectors. According to Aarons and Whitney, (1981), the higher scintillation levels in the EIA region is due to high electron density levels over these latitudes. Next, we shall discuss physical mechanisms that have been proposed in the literature to yield F and E-region low-latitude ionospheric irregularities.

Theoretically, the uplifting of the ionosphere caused by the post sunset enhancement of the zonal electric field allows a sufficiently fast growth of the Rayleigh-Taylor instability (Kelley, 1989). As a result, a spectacular intrusion of plasma density depletions or bubbles into the topside ionosphere occurs and causes plasma density irregularities with sizes ranging from centimeter-scale to kilometer-scale (Basu et al., 1996). In addition to these factors that control the destabilization of the ionosphere, the meridional neutral wind has been shown to have a stabilizing effect on the Rayleigh-Taylor instability. Moreover, Basu et al. (1996) stated that the plasma bubbles originate in the F-region bottom side and become highly structured as they penetrate to altitudes exceeding 1000 km above the magnetic equator. These bubbles extended in altitude map out along the magnetic field to anomaly locations of

$\pm 15^\circ$ magnetic latitudes. Li et al. (2021) stated that during the upward growth of EPB from F region bottomside to topside over the magnetic equator, the large-scale polarization electric field generated within EPB can map to higher latitudes along magnetic field lines, causing similar large-scale structure of density depletion in both hemispheres. Therefore, our observation of high ROT concentrations over the crests of EIA is consistent with these theoretical considerations.

Equatorial plasma density inhomogeneities tend to develop following sunset and may persist throughout the evening but with reduced intensity after local midnight (Goodman, 2005). Our observations in Figure 4, regarding cases of moderate – high irregularities not common over low latitudes, support this statement particularly after local midnight. The daytime occurrence of irregularities in equinox months over low latitudes, presented in Figure 4 and 5, is consistent with the report in the review paper by Aarons (1977). The report indicated daytime scintillations activity over Huancayo in the period March-June and August-October. Aarons (1977) stated that these day-time scintillations are small in amplitude and may represent scattering from the equatorial electrojet. The idea is in line with the existence of equatorial E-region irregularities reported in the literature (Hargreaves, 1992). The equatorial E-region irregularities may be generated due to two-stream instability. This instability may develop within the EEJ region when the east-west drift velocity of the electrons exceeds the ion-acoustic speed (Hargreaves, 1992). The irregularities in the equatorial E-region are strongly field-aligned and exist both during the day and night. Moreover, they are seen as sporadic E on ionograms (Yamamoto et al., 1991).

3.6 Middle latitude irregularities

As seen from Figures 4 and 5, mostly low - moderate ionospheric irregularities occur over our study area during daytime and after sunset. In order to demonstrate that the low - moderate irregularities detected by ROT may be in E-region, we present in Figure 6 simultaneous observations of ROT and critical frequency in E region (foEs) measured by a co-located ionosonde station to the GPS receiver which was used to obtain the ROT data. Since we lacked ROT data of a GPS receiver co-located with an ionosonde station over the current study area, the demonstration was done based on data obtained from stations in Japan which are close to the current study area. The ROT data presented in panel (a) of Figure 6 was obtained using the GPS receiver at Koganei (KGNI), Japan (mag lat 28.46° N) and the foEs data presented in panel (b) was obtained using the ionosonde station at Kokubunji (TO536), Japan (mag lat 29.45° N). The foEs data can be accessed from the National Oceanic and Atmospheric Administration (NOAA) website via the link, <https://www.ngdc.noaa.gov/ftp.html>. To be sure that the high ROT values are not associated with observations at low elevation angles which are prone to multipath effect, we present in panel (c) the elevation angles of the satellites (identified by Pseudo Random Number (PRN))

in view.

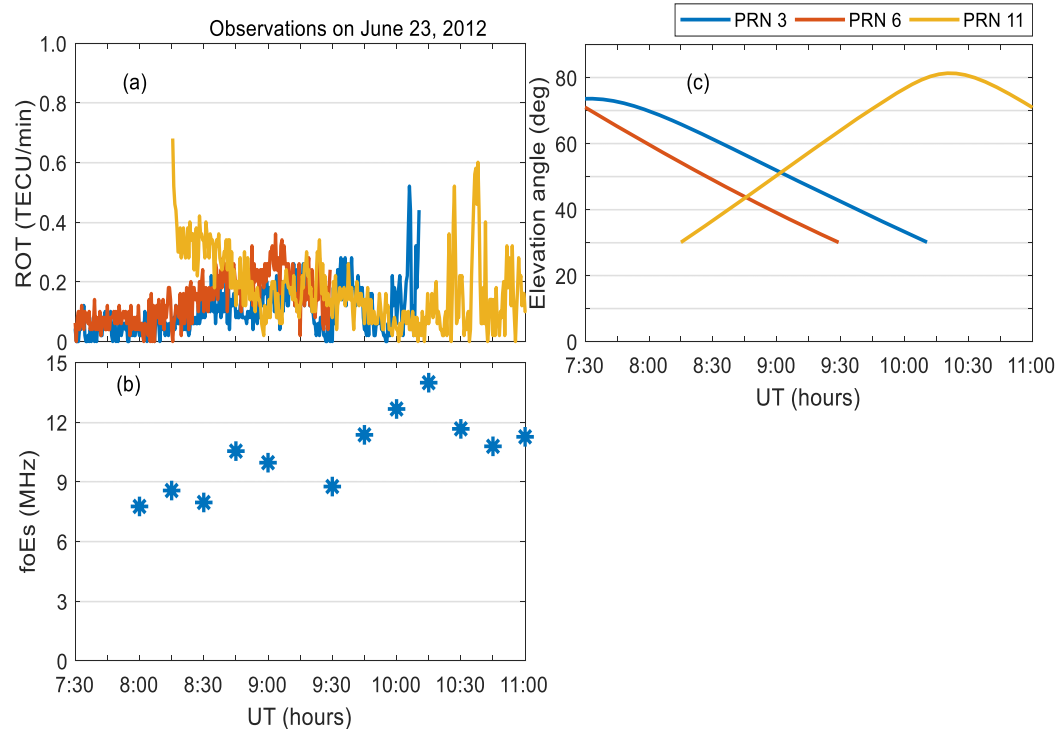


Figure 6: Panels (a) and (c) show ROT over KGNI and the elevation angles of the associated PRNs, respectively, while panel (b) shows foEs over TO536. The observations presented are for June 23, 2012. The blue, red and yellow colors (in panels (a) and (c)) represent data of PRN 3, 6, and 11, respectively.

It is important to mention that Figure 6 is similar to Figure 5 in Mungufeni et al. (2021), except that the former figure presented ROT data while the latter presented ROTI data. Therefore, the idea of presenting in Figure 6 the data on June 23, 2012 followed from the long term simultaneous observations of ROTI and foEs as in Mungufeni et al. (2021). It can be seen in Figure 6 that at around 10:15 UT, foEs values increased and reached ≥ 11 MHz. Such high foEs values are usually associated with intense Sporadic E occurrence that may cause scintillations in microwaves which in turn may degrade GNSS positioning (Maeda and Heki, 2014). Around the time of intense Sporadic E occurrence, ROT values showed moderate ionospheric irregularities ($0.5 \text{ TECU/min} < \text{ROT} \leq 1 \text{ TECU/min}$). As seen in panel (c) the satellite associated with the moderate irregularities was at high ($>60^\circ$) elevation angle. Therefore, Figure 6 shows that some of the moderate ionospheric irregularities detected by ROT may be due to E-region irregularities.

Yamamoto et al. (1991) stated that the irregularities during daytime are distributed below 100 km altitude, while irregularities during the post sunset period appear above 100 km altitude. They inferred that the irregularities are probably produced by the gradient drift instability

acting on electron density gradients related to Es layers. Their inference was based on the study by Ecklund et al. (1981) which found that the 3 m scale size E-region irregularities occur when intense Es patches are known to occur, suggesting that they are generated by the gradient drift instability acting on the large vertical gradients in Es patches. Ecklund et al. (1981) mentioned that gradient drift irregularities are generated when electrons drift horizontally under the influence of an electric field component parallel to the vertical electron density gradient. Basu et al. (1978) showed that between sunset and midnight, 3 m scale irregularities that cause radar backscatter at 50 MHz, co-exist with sub-kilometer scale irregularities that cause VHF and L-band scintillations (Hysell, 2020). Recently, Sun et al. (2021) used high-resolution ROTI to characterize the occurrence of strong Es irregularities over China. They reported that strong Es irregularities tend to occur more frequently around 30°N. Over mid-low latitudes, the irregularities mainly in summer, but can occur in all seasons close to the magnetic equator.

Other studies that have reported mid latitude ionospheric irregularities include Ssessanga et al. (2017), Ding et al. (2011), Miller et al. (1997), and Wang et al. (2019). For instance, Ssessanga et al. (2017) found that F2 region ionospheric irregularities are associated with Medium Scale Traveling Ionospheric Disturbances (MSTIDS). Miller et al. (1997) stated that the ionospheric irregularities over mid latitude regions may be observed as spread F in ionograms. The occurrence of MSTIDS and spread F are usually associated with atmospheric gravity waves (Wang et al., 2019 and Booker, 1971).

4. Conclusions

The latitudinal distribution of ionospheric irregularities over the northern hemisphere and along longitude sector 120 – 130° E was investigated using 7 ground-based GPS receivers and observations of GPS receivers onboard the Swarm satellites. The total electron content (TEC) derived from observations of the GPS receivers were used to compute the rate of change of TEC (ROT) to represent ionospheric irregularities. The speed of the Swarm satellite appears to have a multiplying effect on the ROT observed by the GPS receiver on the satellite. Therefore, the space-based GPS ROT values were normalized using the speed of the satellites. The latitudinal distribution of ionospheric irregularities depicted concentrations around geographic latitude ranges, (i) 1 – 4° N (geomag lat. -8.3 – -5.3° N), (ii) 9 – 34° N (geomag lat. 0.4 – 24.5° N), and (iii) 62.5 – 84° N (geomag lat. 52.9 – 74.4° N). The analysis also revealed that low latitude irregularities during the day can exist in pole-ward direction up to geographic latitude 34° N (geomag lat. 24.5° N). Over high latitudes, ionospheric irregularities during the day and at night can exist in equator-ward direction up to geographic latitudes 74° N (geomag lat. 64.4° N) and 62.5° N (geomag lat. 52.9° N), respectively. Around the time of high sporadic E occurrence, ROT values showed

moderate ionospheric irregularities ($0.5 \text{ TECU/min} < \text{ROT} \leq 1 \text{ TECU/min}$), signifying that some of the irregularities detected by ROT may be related to E-region irregularities.

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The main objectives accomplished

1. Analysis of ionospheric irregularities over South Korea and Japan (mid-latitudes) during the years of 2010 – 2015.
2. Development of a Total Electron Content model over the African region using satellite radio occultation data (COSMIC).
3. Development of a four-dimensional variational (4D-Var) data-assimilation model and its application to the ionospheric disturbances caused by the North Korean rocket (Hwasung-15).
4. Verification of a regional ionospheric assimilation model (IDA4D) with various ionospheric data types.
5. Investigation of the latitudinal distribution of ionospheric irregularities over the northern hemisphere along 120-130 ° E.

List of Publications and any Significant Collaborations that resulted from the AFRL supported project

Papers published

1. Patrick Mungufeni, Sripathi Samireddipalle, Yenca Migoya-Orué, and Yong Ha Kim (2020). Modeling Total Electron Content derived from radio occultation measurements by COSMIC satellites over the African Region, **published:** *Annales of Geophysicae*, 38, 1203-1215, 2020, doi.org/10.5194/angeo-38-1203-2020.
2. Patrick Mungufeni, Yong Ha Kim, Nicholas Ssessenga (2021). Observations of ionospheric irregularities and its correspondence with sporadic E occurrence over South Korea and Japan, **published:** *Advances in Space research*, 67, 2207-2218, <https://doi.org/10.1016/j.asr.2021.01.013>
3. Gwang Su Kim, Yong Ha Kim, Byung-Kyu Choi, Junseok Hong, Nicholas Ssessanga (2021). Characterizing ionospheric disturbances caused by

- the North Korean rocket (Hwasung-15) using a four-dimensional variational (4D-VAR) data-assimilation model, **published:** Journal of the Korean Physical Society, <https://doi.org/10.1007/s40042-021-00282-0>
4. Se-Heon Jeong, Yong Ha Kim, Jeong-Heon Kim, Young-Sil Kwak (2022). A regional ionospheric assimilation study with GPS and COSMIC measurements using a 3D-var algorithm (IDA4D), **published:** Advances in Space Research, 69. 2489-2500, <https://doi.org/10.1016/j.asr.2021.12.049>

Papers in collaboration

1. Ram Singh, Y.S Lee, S.M. Song, Y.H. Kim, J.-Y. Yun, S. Sripathi, B. Rajesh, Ionospheric density oscillations associated with recurrent prompt penetration electric fields during the space weather event of 04 November 2021 over the East-Asian sector, **accepted** in Journal of Geophysical Research.
2. Jeong-Heon Kim, Young-Sil Kwak, Yong Ha Kim, Su-In Moon, Se-Heon Jeong, and Jong Yeon Yun (2021). Potential of Regional Ionosphere Prediction Using a Long Short-Term Memory Deep-Learning Algorithm Specialized for Geomagnetic Storm Period, **published:** Space Weather, 19, e2021SW002741. <https://doi.org/10.1029/2021SW002741>