Ionospheric electron content and NmF2 from nighttime OI 135.6 nm intensity


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This paper derives the theoretical relationship between vertical integrated intensity of OI 135.6 nm oxygen emission with integrated electron content (IEC) from 150 to 800 km altitude as well as $F$ layer peak electron density (NmF2). Local time, seasonal, and solar cycle dependence of the relationship is investigated, and it is proposed as a conversion factor to retrieve IEC and NmF2 values from airglow measurements. The errors associated with the IEC and NmF2 estimation using the derived conversion factor are demonstrated for different local times and solar activity. The theoretical conversion factor is compared with that calculated using airglow measurements by the Global Ultraviolet Imager onboard the Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics mission and the Global Ionospheric Map total electron content as well as the nadir integrated OI 135.6 nm intensity by the Tiny Ionospheric Photometer and NmF2 determined from the Global Positioning System Occultation Experiment, both onboard FORMOSAT-3/COSMIC.


1. Introduction

It is often a challenge to acquire global observation data with sufficient spatial and temporal resolution that is necessary to understand various ionospheric phenomena and also to construct models to explain or predict them. One of the difficulties is to set up and maintain ground facilities, which require huge investment and man power. Global Positioning System (GPS) receivers are very useful in accomplishing this task, providing continuous observations uninterrupted by weather or other observing conditions. Instantaneous snapshots of total electron content (TEC) are provided by Global Ionospheric Map (GIM) using a ground network of GPS receivers. Though GIM gives a fairly well representation of the “real-time” global ionosphere, the practical difficulties in setting up GPS receivers over ocean and other inhabitable regions severely limit the spatial resolution, and necessitate interpolation of the measurements. Also, when receivers of different manufacturers are used, the system bias complicates the comparison of data from an array of worldwide stations. In view of finding an alternative, this work investigates the theoretical relationship between airglow intensity and electron density so that space-based optical remote sensing could be employed to achieve better resolution.

There are several airglow emissions that are used to derive ionospheric parameters. Oxygen emissions at 630.0 nm and 777.4 nm have been used to estimate peak electron density as well as $F$ peak altitude [Tinsley and Bittencourt, 1975; Chandra et al., 1979; Sahai et al., 1981]. However, OI 135.6 nm emission is the one widely used in satellite experiments [Hicks and Chubb, 1970; Barth and Schaffner, 1970; Mendez et al., 2000; Sagawa et al., 2003; Christensen et al., 2003; Kil et al., 2004; Dymond et al., 2000, 2009; Hsu et al., 2009]. The nighttime OI 135.6 nm emission is mainly through the radiative recombination process, and its intensity is hence related to the square of the electron density [Hanson, 1969; Tinsley and Bittencourt, 1975; Meier, 1991]. Several investigations have been carried out to demonstrate the inversion algorithms to retrieve electron density profiles from limb observations of oxygen UV emissions [Picone et al., 1997a, 1997b; Dymond et al., 1997, 2000, 2001; Dymond and Thomas, 2001]. DeMagistre et al. [2004] used the Global Ultraviolet Imager (GUVI) 135.6 nm limb images onboard the Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) satellite to retrieve nighttime electron density profiles. Recently, Dymond et al. [2009] and Hsu et al. [2009] reported the electron density profiles using the Tiny Ionospheric Photometer (onboard FORMOSAT-3 satellites) measurements. The methods followed in these inversions provide the electron density profiles based on a forward model used to simulate the observed data, and are subject to the constraints inherent in the algorithms, and the assumptions and initial conditions involved.
[4] We propose a rather simple method to estimate integrated electron content (IEC) from 150 to 800 km altitude and F layer peak electron density (NmF2) values based on the International Reference Ionosphere (IRI) [Bilitza, 2001], model ionosphere and a nadir measurement of OI 135.6 nm brightness. Since the OI 135.6 nm intensity is proportional to the square of the electron density, there must be some relationship of the intensity with the IEC and NmF2. In this work this relationship is investigated by simulating the emission as well as the corresponding IEC and NmF2 values. The local time (LT), seasonal and solar cycle dependence of this relationship is then discussed, and it is suggested as a conversion factor to retrieve the IEC and NmF2 values from the observations of OI 135.6 nm intensity.

2. Methodology

[5] The primary source of the nighttime OI 135.6 nm intensity is the radiative recombination process of O\(^+\), with a minor contribution from the ion-neutralization of O\(^-\) by O\(^+\) [Meier, 1991], where the O\(^-\) ions are produced through attachment reactions involving atomic oxygen and electron. The OI 135.6 nm volume emission rate (\(v_{1356}\)), including the contributions from radiative recombination and ion-neutralization is given by [Tinsley and Bittencourt, 1975]

\[
v_{1356} = \frac{k_1k_2\beta_{1356}\rho}[e][O^+] + \alpha_{1356}[e][O^+],
\]

(1)

where the values of the reaction coefficients \(k_1\), \(k_2\), and \(k_3\) are \(1.3 \times 10^{-15}\), \(1.0 \times 10^{-7}\), and \(1.4 \times 10^{-10}\) cm\(^3\)s\(^-1\), respectively; the fraction of neutralization resulting in the precursor state (O\(^2\)S) for the 135.6 nm emission, \(\beta_{1356} = 0.54\) [Tinsley and Bittencourt, 1975]; and the radiative recombination rate, \(\alpha_{1356} = 7.5 \times 10^{-13}\) cm\(^3\)s\(^-1\) at 1160K [Meléndez-Alvira et al., 1999]. The \([e]\), \([e]\), and \([O^+]\) densities correspond to the altitude at which the \(v_{1356}\) is determined.

[6] The OI 135.6 nm volume emission is simulated using equation 1, and the vertical column intensity (150–850 km) in Rayleighs (R) is calculated. The electron and O\(^+\) densities, and electron temperature (\(T_e\)) are taken from the IRI-07 model, and the oxygen density from Mass Spectrometer Incoherent Scatter Radar (NRLMSISE-00) model [Hedin, 1991]. The emission is calculated at every 2.5° latitude between −50° to 50°N, and at every 5° longitude and from −180° to 180°E. The simulations are carried out for different local times, seasons, and solar cycle. In order to derive the relationship between the OI 135.6 nm emission with IEC and NmF2, the values between 0 and 30° latitude in each hemisphere are considered. A linear fit of the intensity with the square of IEC, as well as NmF2, implies that the radiative recombination is the dominant process, and the ion-neutralization has only a minor contribution.

[7] Figure 1 displays an example of the OI 135.6 nm intensity, IEC, and NmF2 values simulated for the March equinox of 2002 at 2300 LT between 30\(^\circ\)S and 30\(^\circ\)N over all longitudes. The general features in the emission are similar to those in the IEC and NmF2. The maximum airglow intensity is about 100 R, and is located in the Asian sector at about 25\(^\circ\)N, 60–150\(^\circ\)E. This intensity level agrees with the values reported by TIMED/GUVI and IMAGE/FUV measurements [Henderson et al., 2005; Sagawa et al., 2005]. Figure 1 also demonstrates the similarities in the spatial distribution of the intensity, with that of the IEC as well as NmF2, revealing the interrelationship of the parameters. The scatterplots of the OI 135.6 nm intensity with the square of IEC as well as NmF2 are given in Figure 2. It can be seen that the points are well correlated, falling along a straight line, almost passing through the origin. Slopes of the lines represent the ratio between the square of IEC and NmF2 with the OI 135.6 nm intensity, and give the relationship of the intensity with the IEC or NmF2. In the example shown in Figure 2, the slope or the ratio between square of IEC and the OI 135.6 nm intensity is about 52.6, and is about 10.6 using the square of NmF2. The linear relationship of the OI 135.6 nm intensity with the square of IEC as well as NmF2 implies that the radiative recombination is the dominant process, and the ion-neutralization has only a minor contribution.

[8] Before applying the ratios (Figure 2) to estimate the IEC and NmF2 from the OI 135.6 nm intensity their local time, seasonal and solar cycle variations are investigated. Figure 3 gives the local time variation of the ratio of \((\text{IEC})^2/\text{NmF2}\) with OI 135.6 nm intensity in different months during the years 1995–2005. In general, the local time variation is significant in the equinox months of solar minimum years with the ratio ranging in between 50 and 80 during 2000–2004 LT. In the solar maximum years there is relatively lesser variation of the ratio with an average value of about 55. Figure 4 is the local time variation of the ratio of \((\text{NmF2})^2/\text{IEC}\) with OI 135.6 nm intensity. In comparison to that of the IEC (Figure 3), the local time dependence in this case is less pronounced, especially during the period 2000–2004 LT. Also, there is no distinguishable solar cycle influence. The average value of the ratio is about 10 during 2000–2004 LT, and decreases drastically at earlier and later hours.
Figure 5 displays the ratio of \((\text{IEC})^2\) with the OI 135.6 nm intensity in various months for different local times and different solar activity periods. Seasonal dependence of the ratio can be better visualized here. It can be seen that the seasonal variation is not apparent in the solar maximum years, while the solar minimum years reveal an equinox maximum and summer/winter minimum between 2000 and 0400 LT. In the solar minimum years, the ratio varies between 50 and 80, depending on the season. In Figure 6, the seasonal variation of the ratio of \((\text{NmF}2)^2\) with OI 135.6 nm intensity is demonstrated. The seasonal pattern is less pronounced and is independent of local time and solar activity during 2000–0400 LT, with an average ratio of about 10.

The ratios derived in the above simulations could in principle be used to calculate IEC or NmF2 values from the

Figure 2. The scatterplot showing the relationship between OI 135.6 nm intensity in Rayleighs and the square of IEC simulated using IRI-01 and MSISE-90. The IEC values are given in TECU, and the NmF2 is scaled by $10^{-5}$. All the values between 0 and 30°N latitude at the 2300 LT sector in different longitudes are used in these plots.

Figure 3. The local time variation of the slope for OI 135.6 nm intensity (Rayleighs) with \((\text{IEC})^2\) simulated using IRI-01 and MSIS-90 models for the years from 1995 to 2005.
Figure 4. The local time variation of the slope for OI 135.6 nm intensity (Rayleighs) with $(NmF2)^2$ simulated using IRI-01 and MSIS-90 models for the years from 1995 to 2005.

Figure 5. Seasonal variation of the slope for IEC at different local times during 1995–2005.
Figure 6. Seasonal variation of the slope for NmF2 at different local times during 1995–2005.

Figure 7. Relationship between the ratio of the square of IEC with the OI 135.6 nm intensity and the F10.7 cm solar flux at different local times.
Table 1. The Conversion Factor Between OI 135.6 nm Intensity With (IEC)$^2$ for Different Values of F10.7 cm Solar Flux at Different Local Times

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<td>49.44</td>
<td>41.54</td>
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Given values of the OI 135.6 nm emission. The local time, seasonal and solar cycle differences of the ratio, especially for the IEC, suggest that it is more suitable to define a set of ratios for appropriate observing conditions, rather than relying on a single value. To further investigate the solar activity dependence of the local time and seasonal variation of the ratio of (IEC)$^2$ with OI 135.6 nm intensity, the ratio during the years 1995–2005 at different local times is plotted as a function of F10.7 solar flux. Figure 7 displays the variation of the ratio with F10.7 at 0200 LT. When F10.7 > 150, the ratio is more or less constant with the increase in solar flux, while for F10.7 < 150 it tends to increase when the solar flux decreases. The decrease is gradual when F10.7 values are between 150 and 100, and becomes very drastic when F10.7 falls below 100. This indicates that the variation of the slope needs to be considered at least for three different sets of values of F10.7, namely, F10.7 > 150, 150 > F10.7 > 100, and F10.7 < 100. Hence, to arrive at a quantitative estimate of the ratio so that it can be used as a conversion factor, its value at every hour in the period 1800–0600 LT, in each month is given. The table shows a comparison of the IEC and the simulated OI 135.6 nm intensity, and the IEC from the IRI electron density profiles (IRI-IEC), are compared with the IEC estimated from the simulated emission (estimated IEC), using the corresponding conversion factor from Table 1. Figure 9 gives the IEC, estimated IEC, the difference between the IRI-IEC and the retrieved IEC, as well as the percentage difference, at 2200 and 0200 LT for the years 1996 and 2002, respectively. It can be seen that there is an overall good agreement between the IRI-IEC and the estimated

The ratio of (NmF2)$^2$ with the emission as a function of F10.7 flux at 0200 LT. It can be seen that, in this case the solar activity variation is negligible and is not considered in Table 2, where the ratio at different local times in each month is given. The values in Tables 1 and 2 can be used as a conversion factor to derive IEC or NmF2 values from the nadir measurements of OI 135.6 nm intensity.

[11] In order to examine how well a single measurement of OI 135.6 brightness represents the model IEC and NmF2 using conversion factors, the simulated OI 135.6 nm and the IEC from the IRI electron density profiles (IRI-IEC), are compared with the IEC estimated from the simulated emission (estimated IEC), using the corresponding conversion factor from Table 1. Figure 9 gives the IEC, estimated IEC, the difference between the IRI-IEC and the retrieved IEC, as well as the percentage difference, at 2200 and 0200 LT for the years 1996 and 2002, respectively. It can be seen that there is an overall good agreement between the IRI-IEC and the estimated
IEC. Note that the two IEC values differ in magnitude only within ±4 IECU, which can also be seen in the very small percentage difference between the two. The estimated IEC using the conversion factor is within 10% of the IRI-IEC in solar maximum and within 20% in solar minimum. Figure 10 displays the accuracy of NmF2 retrieval. Again, the deviation from the IRI-NmF2 and the estimated NmF2 is mostly within 20%.

The conversion factor introduced and described above has been validated with the help of two separate sets of measurements. For the IEC, the OI 135.6 nm disk measurement by GUVI onboard TIMED satellite and the ground based TEC values derived from GIM are used. Figure 11 gives the result using GUVI and GIM data during 2000–0100 LT, for the solar maximum year 2002. In order to have a better signal-to-noise ratio in the airglow data, only the measurements over the equatorial ionization anomaly (EIA) zone are considered. Since this restricts the number of data points, all the available observations in entire year 2002 are used in Figure 11. Similarly, the conversion factors calculated for the solar minimum year 2006 are given in Figure 12. The conversion factor is about 50–70 for both the years and it agrees with the range of the corresponding theoretical values with an error about 25% in solar maximum and about 30% in solar minimum. In Figure 13, the conversion factor using OI 135.6 nm intensity measured by Tiny Ionospheric Photometer (TIP) and the NmF2 determined from GPS Occultation Experiment (GOX) electron density profiles are displayed. Both the instruments are onboard the FORMOSAT-3/COSMIC satellites. Note that the values calculated from the observation in this case agree well with that using the model and simulation.

The difference in the conversion factor from the observation data with that of the theoretical value in Figures 11 and 12 could be partly because of the difference in the range of altitudes used for the IEC and TEC integration. The IEC integration is between 150 and 800 km regions, whereas the GIM gives TEC from the receiver to the satellite altitude of over 21,000 km. Moreover, the seasonal variation of the conversion factor also might influence. In addition, the noise in the observation could add to the differences and contribute to the scatter of the data points. In order to quantify the statistical error in the estimated conversion factor, the 1 sigma uncertainty of the fit of the data points between GUVI and GIM are given in Table 3. There is about 68.2% probability that the estimated conversion factors are true with an uncertainty of about 5–7% in solar maximum and 5–10% in solar minimum. Figure 14 gives an example for the estimation of IEC from the GUVI measurement of OI 135.6 nm for two different levels of solar activity. Though the general features in both IEC and TEC appear very similar, there is large difference in the values at certain locations. For example, one could see localized regions of very intense airglow, and hence the IEC, at about 30–40°E and 120–160°E, between 20 and 30°N, and an extended region of less intensity between 60°W and 60°E in Figure 14 (top). Similar disagreements are present in Figure 14 (bottom) also. Note that the GIM TEC is over a latitude-longitude grid of 2.5° × 5°, and employs interpolation when ground stations are limited, while GUVI makes measurements at very high resolution.
through the products are averaged to match with GIM. Thus the longitudinal features could get smeared out in the GIM TEC compared to more sensitive airglow measurement. Except for such locations, the estimated IEC is within 30% of the GIM TEC, which also includes the systematic difference between the two due to the difference in the altitude coverage.

4. Discussion and Conclusion

[14] The method described in this work demonstrates that a simple conversion table based on the relationship of OI 135.6 nm airglow and the electron density can be applied to estimate the IEC and NmF2 values. The conversion table depends only on the photochemistry model used and is not biased by any assumptions or initial conditions. However, the conversion factor exhibit local time, seasonal and solar cycle variation of electron density. This is illustrated in Figure 15, which displays the altitude profiles of electron density and the OI 135.6 nm layers are about 193 and 134 km in 2002, while they are about 217 and 121 km in 2006, respectively. The electron density profile in fact has larger thickness in the solar minimum, while the emission layer of F10.7 < 100 will reflect in the column intensity and also in the ratio. As a result, the emission will fall off more rapidly at altitudes above or below the F peak position than that of the electron density. In other words, the altitudinal range with significant contribution to the integrated values of the OI 135.6 nm intensity would depend on the vertical distribution of the electron and atomic oxygen ion density. Hence the local time, seasonal as well as solar cycle variation of electron density will reflect in the column intensity and also in the ratio.

[15] This is illustrated in Figure 15, which displays the altitude profiles of electron density and the OI 135.6 nm volume emission rate in the equinox period (March) for high (2002) and low (2006) solar activities at different local times. At 2000 LT, the half widths of the electron density and the OI 135.6 nm layers are about 193 and 134 km in 2002, while they are about 217 and 121 km in 2006, respectively. The electron density profile in fact has larger thickness in the solar minimum, while the emission layer thickness is smaller, and as a result the slope is more than that in solar maximum. Figure 16 gives the local time and seasonal as well as solar cycle variation of the differences in the half widths of the electron density at each altitude (\[ \frac{d}{dh} \int [n_i(h)]^2 \, dh \]), compared with the square of the sum of the electron density (\[ \int n_i(h) \, dh \]). Note that there is a quadratic relationship between the electron density and the emission. As a result, the emission will fall off more rapidly at altitudes above or below the F peak position than that of the electron density. In other words, the altitudinal range with significant contribution to the integrated values of the OI 135.6 nm intensity would depend on the vertical distribution of the electron and atomic oxygen ion density. Hence the local time, seasonal as well as solar cycle variation of electron density will reflect in the column intensity and also in the ratio.
Figure 9. Error involved in the estimation of IEC for (top) 1996 at 2200 and 0200 LT and (bottom) the same local times in 2002. The first panel is the Simulated OI 135.6 nm intensity, the second panel is the IEC from IRI, the third panel is the estimated IEC from the emission using the appropriate conversion factor, the fourth panel is the difference between the values in the second and third panels, and the fifth panel is the percentage difference between the second and third panels.
Figure 10. Same as Figure 9 but for NmF2. Note that NmF2 is in cm$^{-3}$ and is scaled by $10^{-5}$.
Figure 11. Conversion factor using OI 135.6 nm intensity measured by TIMED/GUVI and the square of GIM TEC for the year 2002 during 2000–0200 LT. For a better signal, only those observations made over the EIA region are selected.
Figure 12. Conversion factor using OI 135.6 nm intensity measured by TIMED/GUVI and the square of GIM TEC for the year 2006 during 2000–0200 LT. For a better signal, only those observations made over the EIA region are selected.
the electron density and the OI 135.6 nm emission with that of the conversion factor. It can be seen that both the conversion factor for IEC and the half width difference exhibit a similar pattern, revealing their relationship. However, the local time variation, especially in the early morning period, does not show a close agreement. Since the OI 135.6 nm profile in the early morning periods were very weak, the half width estimation during this period is less accurate, and could be partially the reason.

It should be noted that the conversion table described here depends on the model used for the ionospheric data as well as the airglow simulation. The calculated values are limited by the IRIs ability to accurately represent the range of electron density shapes encountered in the real ionosphere. The basic representation of electron density in IRI is a Chapman layer and the primary database from which the electron density profiles are drawn are derived from ionosondes, which when used in bulk have a rather limited ability to resolve profile shapes. The Chapman layer shape is highly idealized, particularly for electron densities at night, since the lifetimes are long and the transport is an important process. In spite of all these constraints, the fairly good agreement of the observation data with that of the model and simulation suggests that the conversion table represent the relationship between the ionospheric parameters and the measured intensity.

Figure 13. Conversion factor using OI 135.6 nm intensity measured by TIP and the square of GOX NmF2 in different months for the year 2009 at 2100 LT.
In conclusion, the good agreement with observation data shows that the conversion table proposed in this work provides a simple method to estimate IEC and NmF2 from vertical integrated OI 135.6 nm intensity. It is possible to have highly sensitive airglow measurements, enabling accurate determination of electron density gradients, which could significantly improve the spatial resolution of existing global ionospheric maps. Moreover, the IEC and NmF2 values retrieved using the conversion factors could serve as more realistic initial parameters to other sophisticated algorithms that are currently used for electron density retrievals and tomography.

Table 3. The 1σ Uncertainty of the Fit of the GUVI Radiance and GIM TEC in Figures 11 and 12

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<td>59.5</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Figure 14. Error involved in the estimation of IEC from GUVI OI 135.6 nm intensity and GIM TEC for (top) high solar activity (F10.7~160) period on 22 September 2002 and (bottom) moderate solar activity (F10.7~125) on 20 January 2004. Both the observations are taken at about 2300 LT, between 0 and 30° N geographic latitude. The first panel is the GUVI OI 135.6 nm intensity, the second panel is the GIM TEC, the third panel is the estimated IEC from the emission using the appropriate conversion factor, the fourth panel is the difference between the values in the second and third panels, and the fifth panel is the percentage difference between the second and third panels.
Figure 15. The local time and solar activity difference in the vertical distribution of the electron density (dotted) as well as the OI 135.6 nm volume emission (solid) simulated using IRI-01 and MSIS-90 models for the equinox period, illustrating the variation of the layer thickness.

Figure 16. The solar cycle and local time variation of the difference between the half widths of the electron density and OI 135.6 nm profiles (dashed). The values of the slope as well as the \((\text{IEC})^2\), \((\text{NmF2})^2\), and OI 135.6 nm intensity are also shown.
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