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# ELECTRON DENSITY IN THE F1 LAYER OVER NORILSK IN 2007–2014

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**Abstract.** We report the results of the analysis of annual variations in daily electron density (*N*) for various solar activity conditions — minimum, rise, and maximum (2007–2014) — obtained from digisonde measurements at the ionospheric station Norilsk (69.4° N, 88.1° E). New coefficients of the known semi-empirical model (SEM) describing the connection between *N* and thermosphere characteristics are calculated to identify regularities of these variations exactly at Norilsk station. The height changes of annual variations in the noon electron density *N* are obtained in the F1-region (120–200 km). The experimental data approximation describes *N* quite satisfactorily at these heights in the daytime of different seasons under different solar activity conditions. It is shown that in the years of solar minimum at all heights of the F1 layer the tendency remains for maximum *N* in summer and for minimum *N* in winter. In later years and in the year of maximum solar activity, a characteristic feature of the behavior of *N* is the change in the phase of the annual variation by 180° in the range of heights from 170 to180 km: maximum *N* is observed in winter; and minimum, in summer.

**Keywords:** annual variations, electron density, semi-empirical model.

## INTRODUCTION

The structure of the semi-empirical model (SEM), which analytically describes the relationship of electron density *N* with thermosphere characteristics [Shchepkin et al., 1997], has been previously developed by the authors. Numerous calculations have shown good agreement between the model and experiments. It should be noted that the general nature of the *N* dependence on gas composition and temperature of the thermosphere makes it possible to use SEM for describing the *N* behavior at heights 120–200 km under different solar and geomagnetic activity conditions at different geographical sites in middle and high latitudes [Shchepkin et al., 2005, 2007, 2008]. It is convenient to examine *N* variations of this type, using calculations with the semi-empirical model. Thus we can easily identify variations associated with season, time of day, level of solar activity, as well as track longitude/latitude changes.

The *N* data array obtained below the F2-layer maximum with a digisonde at Norilsk station allows us to analyze the collected experimental material. The paper deals with regular daily hourly values of *N* in the height range from 120 to 200 km, where in most cases during the daytime hours the photochemical balance condition holds. Note that the term “F1 layer” should be applied to the height range from 120 to 200 km, where in favorable conditions this layer is formed.

We analyze annual variations in the noon electron density at the said heights during minimum, rise, and maximum of solar activity (2007–2014). We examine deviations of the calculated values $N_{cal}$ from the experimental ones $N_{exp}$ in different months of these years and discuss their possible causes. Notice that the results are valid within the frameworks of the atmospheric model NRLMSISE-00 [Picone et al., 2002] for respective neutral gas variations.

## MODEL CALCULATIONS

At fixed F1-layer heights, *N* can be described by the analytical relation [Shchepkin et al., 2008]

$$N/N_{av}=x_1+x_2([O]/(5[O_2]+[N_2]))^{1.5}+x_3([O]/[N_2])^{0.5}\cos(\chi)^{0.5}+x_4\exp(-(T-600)/600)+x_5(E/E_0). \quad (1)$$

Here $N_{av}$ is the average value of *N* over the entire data volume separately for each height; $x_j$ represents the coefficients of equation (1); $\chi$ is the solar zenith angle; $E_0$ is the ionizing radiation flux energy *E* during sunspot maximum. Values of *E* are calculated by the model [Tobiska, Eparvier, 1998]. Densities of neutral particles [O], [$O_2$], and [$N_2$] and temperature *T* are computed using the neutral atmosphere model NRLMSISE-00 [Picone et al., 2002]. To obtain the $x_j$ coefficients of equation (1), we take an array of daily hourly values of *N* measured with the digisonde at heights of 120, 130, ..., 190, 200 km at Norilsk station in 2003–2014 from 7 to 18 LT. The thermosphere characteristics and *E* values are calculated from both daily *F*10.7 index values (in units of $10^{-22}$ W $m^{-2}Hz^{-1}$) and its values averaged over 81 day (three solar rotations). The geomagnetic activity level is taken into account using daily 3-hour values of $A_p$ [http://wdc.kugi.kyoto-u.ac.jp]. Hence, we obtain coefficients of approximation equation (1) for minimum, rise, and maximum of solar activity, which contribute greatly to the current SEM version. Table 1 lists coefficients during solar minimum at Norilsk station.

Table 1

Coefficients of approximation equation (1)

| $h$, km | $N_{av}\cdot10^4$ cm$^{-3}$ | $x_1$ | $x_2$ | $x_3$ | $x_4$ | $x_5$ |
|---|---|---|---|---|---|---|
| 120 | 7.51 | –0.1844 | –7.403 | 4.842 | 0.0000 | 0.9708 |
| 130 | 8.57 | –0.4140 | –7.960 | 5.459 | 0.2335 | 0.9473 |
| 140 | 10.25 | –0.3128 | –8.238 | 5.310 | 0.2341 | 0.7888 |
| 150 | 12.07 | –0.3352 | –7.917 | 5.106 | 0.4142 | 0.7005 |
| 160 | 13.80 | –0.3521 | –7.048 | 4.688 | 0.5798 | 0.7009 |
| 170 | 15.39 | –0.3646 | –5.463 | 4.130 | 0.7145 | 0.7496 |
| 180 | 17.16 | –0.3462 | –2.644 | 3.430 | 0.7984 | 0.7455 |
| 190 | 19.19 | –0.3267 | 1.388 | 2.659 | 0.8516 | 0.7008 |
| 200 | 22.32 | –0.3604 | 5.298 | 1.983 | 0.9051 | 0.7580 |

## RESULTS

The typical curves of noon $N_{cal}$ annual variations at 150, 180, 190, and 200 km for Norilsk station (69.4° N, 88.1° E), calculated for the period of interest (2007–2014), are shown in Figure 1. As an example, we have chosen the year of maximum solar activity — 2014. By comparison, experimental $N_{21}$ values are given for each height, i.e. $N_{exp}$ averaged over 21 days across the entire data set (±10 days centered at a given point). For all the heights there is sufficiently good agreement between the calculated and experimental curves of $N$ both in values and in shape.

At low heights (150 km), maximum $N_{cal}$ values are well-defined in summer; and minimum ones, in winter. Such a shape of $N(D)$ curves ($D$ is the number of day in the year) is typical for heights 140–170 km. At 190 and 200 km, the maximum $N_{cal}$ values generally occur in winter; and minimum annual variations, in summer.

The $N(D)$ curves of one type are transformed into curves of another type near 180 km. There is the lowest amplitude of annual variations at this height. The described changes in the shape of annual $N$ variations are caused by vertical variations in gas composition, which occur against a change in the electron density dependence of ionospheric charged particle neutralization rates.

Lack of data at all the heights at the end of the year ($D$ = 300, 330, 360) is explained by the fact that in winter in this height range the experimental values of $N$ are small and unreliable. Note also that the numerous gaps and absence of data in the studied $N$ arrays in these years in Norilsk lead to the fact that the correlation coefficients between the arrays of calculated and experimental values of $N$ for this period are within 0.94–0.70, with the highest value corresponding to the height of 120 km; and the lowest, to the height of 200 km. This results in a difference between $N_{cal}$ and $N_{21}$ at 190 and 200 km.

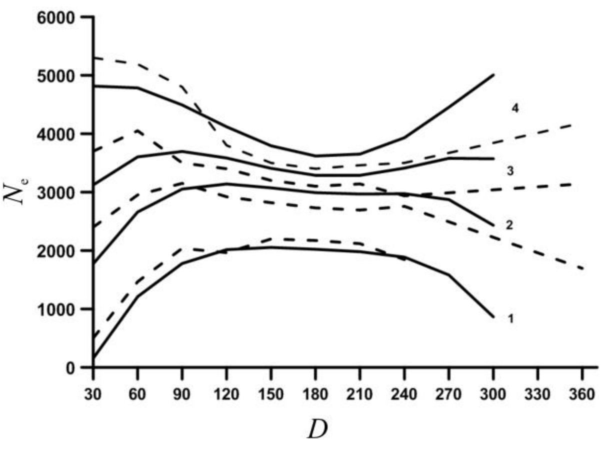


*Figure 1.* Annual variations in noon $N_{cal}$ values in 2014 at several heights: 150 km (1); 180 km (2); 190 km (3); 200 km (4). The dashed line shows averaged experimental values of $N_{21}$. Along the X-axis are days of the year

We can observe some differences in the annual behavior of electron density in Norilsk during minimum solar activity: in general, according to SEM calculations, at all the heights the tendency remains for maximum $N$ in summer, which is confirmed by experimental values. In other years (2010–2014) of the period under study, the change of the $N(D)$ curves corresponds to the above behavior in 2014.

Figure 2 shows the annual variations in noon $N_{cal}(D)$ calculated for 150, 180, and 200 km heights. For each height, $N_{cal}$ values correspond to three selected years: 2009 (minimum), 2012 (rise), and 2014 (maximum). Values for one specific height are shown in the Figure according to variations in $F$10.7, which grew from 2010 to 2014 (Table 2). The $N_{cal}(D)$ curves for 2014 are at the

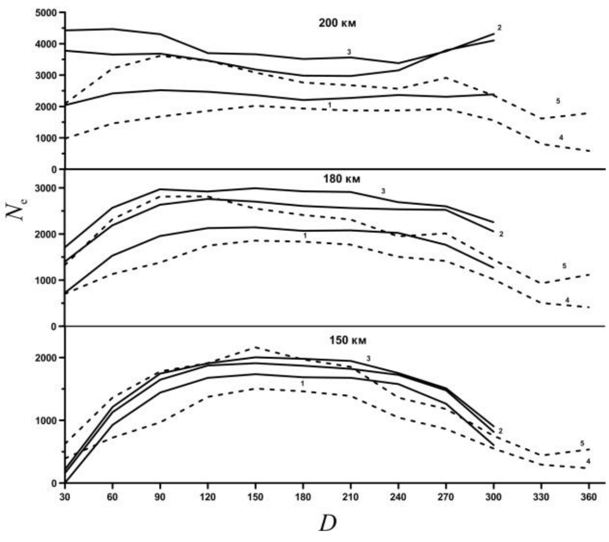


*Figure 2.* Annual variations in noon $N_{cal}$ at 150 km, 180 km, and 200 km for three years: 2009 (1), 2012 (2), 2014 (3). Dashed lines indicate the $N$ values obtained by the IRI model at each height for 2009 (4) and 2014 (5). Along the X-axis are days of the year

top of the Figure; those for 2009, at the bottom.

Figure 2 also depicts the annual variations in noon $N$ for 2009 and 2014, which were calculated by the IRI model [Bilitza et al., 2017] for the above heights. The similarity with the calculated $N$ variations of interest lies in the fact that the summer maximum is observed at 150 km for all the years considered.

The difference between the $N$ variations calculated by IRI and those calculated by SEM is in the presence of two maxima in curves of annual variations at 180 and 200 km during equinoxes, with the spring maximum being much higher than the fall one. This shape of the IRI curves corresponds to all the years considered.

This is not observed for SEM curves of $N(D)$. The phase in the annual cycle of $N$ is reversed at ~180 km. This is confirmed by experimental values (see Figure 1). Our results differ from those obtained with IRI — the $N$ values calculated by IRI are lower almost for all the heights considered of the period under study.

In general, we can speak of a good approximation of most experimental material. As an example Table 3 shows calculated $N_{cal}$ and experimental monthly average $N_{exp}$ (daytime) values of electron density for April and June of the selected three years (2007, 2012, and 2014) at two heights (150 and 190 km). The data (see Table 3) show that the experimental values are quite reasonably consistent with the calculated values. At the same time, at 190 km $N_{cal}$ differ from $N_{exp}$. Reasons of this difference have been discussed above.

Deviations $dN$ of monthly average $N_{cal}$, obtained by averaging daily values for each local hour, from experimental ones were computed from the formula

$$dN=(N_{cal}-N_{exp})/N_{exp}.$$

Table 4 shows deviations $dN$(%) at 150 and 190 km in some months of 2007.

During forenoon hours, $N_{cal}$ exceed $N_{exp}$ at 150 and 190 km in all months; in the afternoon and in the evening, vice versa. A reason of this may be calculation errors at large (>70°) solar zenith angles for early morning and evening hours, as well as peculiarities of gas composition deviation from its model description [Shchepkin et al., 2008]. In particular, in winter the evening effect at high altitudes of the range under study may be due to the increased atomic oxygen density as compared to that adopted in the model.

Table 2

Annual average $F$10.7 in 2007–2015

| Year | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 |
|---|---|---|---|---|---|---|---|---|---|
| $F$10.7 | 74 | 69 | 71 | 80 | 113 | 120 | 123 | 146 | 118 |

Table 3

Monthly average $N_{exp}$ and calculated $N_{cal}$ at 150 and 190 km ($N \cdot 10^4$, cm$^{-3}$) for local daytime hours

| year | parameter | April | | | | | | | June | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 150 km | | | | | | | | | | | |
| | | 8 LT | 10 LT | 12 LT | 14 LT | 16 LT | 18 LT | 8 LT | 10 LT | 12 LT | 14 LT | 16 LT | 18 LT |
| 2007 | $N_р$ | 12 | 15 | 16 | 15 | 12 | 10 | 14 | 16 | 18 | 17 | 15 | 12 |
| | $N_э$ | 10 | 13 | 15 | 16 | 14 | 10 | 13 | 16 | 18 | 17 | 16 | 14 |
| 2012 | $N_р$ | 13 | 16 | 18 | 17 | 14 | 10 | 15 | 18 | 19 | 18 | 16 | 13 |
| | $N_э$ | 12 | 15 | 18 | 16 | 13 | 10 | 16 | 18 | 19 | 18 | 16 | 15 |
| 2014 | $N_р$ | 14 | 17 | 19 | 18 | 15 | 10 | 16 | 19 | 20 | 19 | 17 | 14 |
| | $N_э$ | 15 | 18 | 19 | 19 | 15 | 10 | 19 | 20 | 22 | 22 | 19 | 14 |
| 190 km | | | | | | | | | | | | | |
| 2007 | $N_р$ | 18 | 21 | 22 | 22 | 19 | 15 | 19 | 21 | 22 | 22 | 20 | 17 |
| | $N_э$ | 15 | 18 | 20 | 22 | 21 | 18 | 18 | 20 | 22 | 21 | 20 | 20 |
| 2012 | $N_р$ | 24 | 28 | 30 | 30 | 27 | 22 | 24 | 27 | 28 | 28 | 26 | 23 |
| | $N_э$ | 20 | 25 | 28 | 27 | 25 | 17 | 24 | 26 | 28 | 27 | 28 | 22 |
| 2014 | $N_р$ | 29 | 33 | 35 | 34 | 31 | 26 | 28 | 31 | 32 | 32 | 30 | 27 |
| | $N_э$ | 23 | 27 | 29 | 29 | 26 | 20 | 26 | 27 | 29 | 28 | 27 | 24 |

Table 4

$dN$ (%) at 150 and 190 km in 2007

| 150 km | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| month / LT | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| February | – | – | – | – | 34 | 18 | –11 | –30 | –41 | – | – | – |
| March | – | – | – | – | 34 | 24 | 20 | 7 | –4 | –25 | –33 | –50 |
| April | – | 33 | 25 | 16 | 9 | 4 | 1 | –4 | –7 | –11 | –11 | –25 |
| June | 18 | 9 | 7 | 2 | –2 | –5 | –1 | –2 | –3 | –7 | –12 | –12 |
| September | – | – | – | 36 | 23 | 17 | 9 | 7 | 1 | 3 | –14 | –23 |
| 190 km | | | | | | | | | | | | |
| February | – | – | – | – | 11 | –6 | –20 | –31 | –33 | –36 | 13 | – |
| March | – | – | – | 25 | 9 | – | –5 | –14 | –17 | –29 | –29 | –22 |
| April | 30 | 18 | 17 | 16 | 12 | 8 | 4 | –3 | –8 | –12 | –14 | –19 |
| June | 11 | 9 | 8 | 7 | 5 | 2 | 2 | 2 | 1 | –3 | –7 | –11 |
| September | – | 45 | 21 | 17 | 13 | 4 | –1 | –7 | –7 | –10 | –20 | –21 |

## CONCLUSION

The use of the semi-empirical model describing the relationship between electron density and thermosphere characteristics, solar zenith angle, and ionizing radiation flux intensity allowed a detailed analysis of the behavior of the ionosphere below 200 km under different solar activity conditions.

The obtained coefficients of the SEM regression equation for Norilsk station are consistent with specific conditions of minimum, maximum, and rise of solar activity at Norilsk station and are important complements to the model.

The approximation of the *N* array allowed us to examine the annual electron density variations at Norilsk station for the period from 2007 to 2014. We have shown that during years of minimum solar activity at all F1-layer heights, the tendency remains for maximum values of *N* in summer; and for minimum ones, in winter. In subsequent years and in the year of maximum solar activity, a characteristic feature of the *N* behavior is the change in the phase of the annual variation by 180° in the height range of 170 to 180 km: maximum values are observed in winter; and minimum, in summer.

Further collection of experimental data will allow us to develop a more complete version of SEM for different geoheliophysical conditions. This model is important, in particular, for evaluation of gas composition of the thermosphere from ionospheric measurements.

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