Influence of the periodic changes in the incoming solar hydrogen Ly-α radiation intensity on the total electron content in the ionospheric D-region

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Abstract

This paper analyzes variations in the total electron content in the D-region induced by periodical changes in the solar hydrogen Lyα radiation. The considered changes are a consequence of variations in the solar radiation intensity during a solar cycle and a consequence of the Earth's revolution. The presented analysis is based on the Quiet ionospheric D-region (QIonDR) model, which shows the dependencies of ionospheric parameters on the smoothed daily sunspot number and season. We consider the vertical and slant (for different zenith angles) total electron content in the D-region (TEC_D) which are important for calculations of delays of satellite signals. The obtained results show a significant influence of the considered zenith angle and period of the solar cycle and season on calculating the considered ionospheric parameter.

Introduction

The ionosphere is an ionized part of the Earth's atmosphere that extends from approximately 60 km to 1000 km above the Earth's surface. Due to the high complexity of the ionosphere, the electron density is not uniform for all altitudes. Consequently, we can identify three ionospheric regions: D-, E-, and F-region.

The Earth's atmosphere, and therefore its ionized part, is permanently exposed to external (outer space) periodic and non-periodic influences. Some of the periodical effects have a significant role in complex chemical processes. Thus, variation in the solar hydrogen Lyα radiation has a dominant contribution to the free-electron production rate variation in photo-ionization processes in the D-region.

In this paper, we analyze periodical variations in the influence of the solar hydrogen Lyα photons on the production of the free electrons described by the D-region total electron content (TEC_D).

Total electron content modeling

The total electron content (TEC) is an ionospheric parameter characterized by the impact of the ionosphere's state on electromagnetic wave propagation. TEC represents the total number of electrons in a column with a 1 m^2 cross-section area along the signal path from a transmitter (satellite) to the receiver. TEC is expressed in Total Electron Content Units (TECU), which amounts to 10^{16} free electrons per squared meter.

TEC is usually calculated using appropriate models, such as the single-layer models (SLM) or multiple-layer models (MLM). SLMs assume that the ionosphere is a thin shell at a specific height (typical height value is between 300 km and 400 km). On the other side, MLMs consider numerous thin shells at specific heights instead of one thin shell.

Mathematically, TEC is defined by the following integral (Hofmann-Wellenhof et al., 2008, Seeber, 2003):

$$\mathrm{TEC}(t) = \int_S^R N_e dh, \quad (1)$$

where N_e stands for the electron density, h is the altitude, and S and R are the bottom and top ionosphere boundaries, respectively. Within the same spirit, for the top and bottom boundaries of the D-region, i.e., h_t = 90 km and h_b = 60 km, as limits of integration, the total electron content in the D-region, $\mathrm{TEC_D}$, can be expressed as:

$$\mathrm{TEC_D}(t) = \int_{h_b}^{h_t} N_e dh. \quad (2)$$

The previous equation stands for $\mathrm{TEC_D}$ determination if the signal path goes perpendicular to the D-region boundary, i.e., for 0° zenith angle. For other cases, the slant $\mathrm{TEC_D}$ ($\mathrm{STEC_D}$) is introduced based on the value of $\mathrm{TEC_D}$ and the corresponding mapping function $S(\theta)$ for the defined zenith angle θ:

$$\mathrm{STEC_D}(t) = S(\theta) \cdot \mathrm{TEC_D}(t) = \frac{\mathrm{TEC_D}(t)}{cos\theta}. \quad (3)$$

As we can see in Eq. (2), $\mathrm{TEC_D}$ can be determined based on N_e, which can be calculated using Wait's model of the ionosphere (Wait & Spies, 1964). This model assumes the horizontally uniform ionosphere described by two so-called Wait's parameters: the "sharpness" (β) and the signal reflection height (H'). N_e can be calculated according to expression (Thomson, 1993):

$$N_e(\beta, H', h) = 1.43 \cdot 10^{13} \cdot e^{-\beta(\sigma,\chi)H'(\sigma,\chi)} \cdot e^{[\beta(\sigma,\chi)-0.15]h}, \quad (4)$$

where Wait's parameters in the midday periods for the D-region above Central Europe can be determined using Eqs. (Nina et al., 2021):

$$H'(\sigma,\chi) = 74.74 - 0.02984\sigma + 0.5705cos(2\pi(\chi - 0.4712) + \pi), \tag{5}$$

and

$$\beta(\sigma,\chi) = 0.2635 + 0.002573\sigma - 9.024\cdot 10^{-6}\sigma^2 + 0.005351cos\big(2\pi(\chi - 0.4712)\big). \tag{6}$$

Here, σ and χ are the smoothed daily sunspot number and season parameter, which, multiplied by 365, deliver a day in a year, respectively. In these equations, β and H' are given in km^{-1} and km, respectively.

According to Eqs. (2) and (4), TEC_D can be determined using the expression (Todorović Drakul et al., 2016):

$$\mathrm{TEC_D}(t) = 1000\frac{N_e(\beta,H',h_t) - N_e(\beta,H',h_b)}{\beta(\sigma,\chi) - 0.15}. \tag{7}$$

Analysis and results

In this contribution, we calculate TEC_D and $STEC_D$. Calculations are performed for 365 days and different values of σ in the range of 20 to 120 with a step equal to 20. TEC_D for all seasons and different values of σ are given in Fig. 1, where it is seen that TEC_D has maximal values in the period of the summer solstice and that increase with σ. The intensity of variations during a year increase with σ. The obtained values of TEC_D reach near 0.04 TECU.

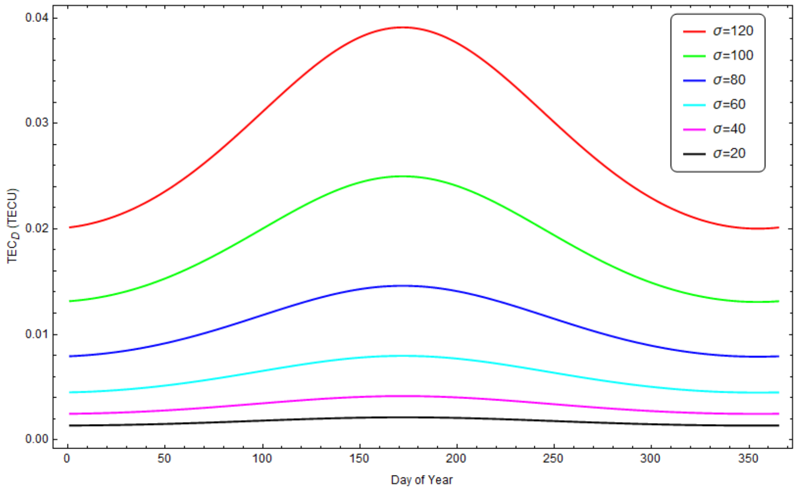

Fig. 1. Dependency of TEC_D on the day of the year for different σ.

$STEC_D$ is calculated based on TEC_D values and the zenith angle of 70°. Those results are given in Fig. 2, where one can see that the properties of the obtained dependencies are the same as for TEC_D.

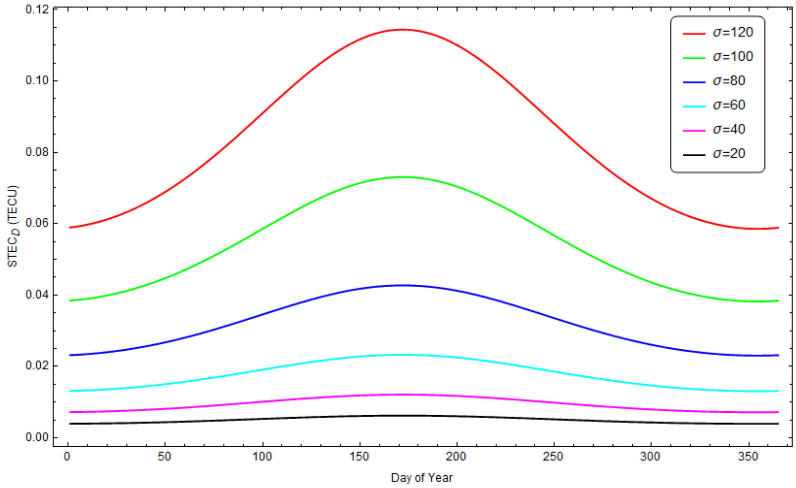

Fig. 2. Dependency of $STEC_D$ on the day of the year for $\theta = 70^o$ and different σ.

Comparisons of TEC_D and $STEC_D$ for the same σ are given in Fig. 3. Those comparisons show that $STEC_D$ has larger values than TEC_D for all values of σ, and that difference decrease with σ.

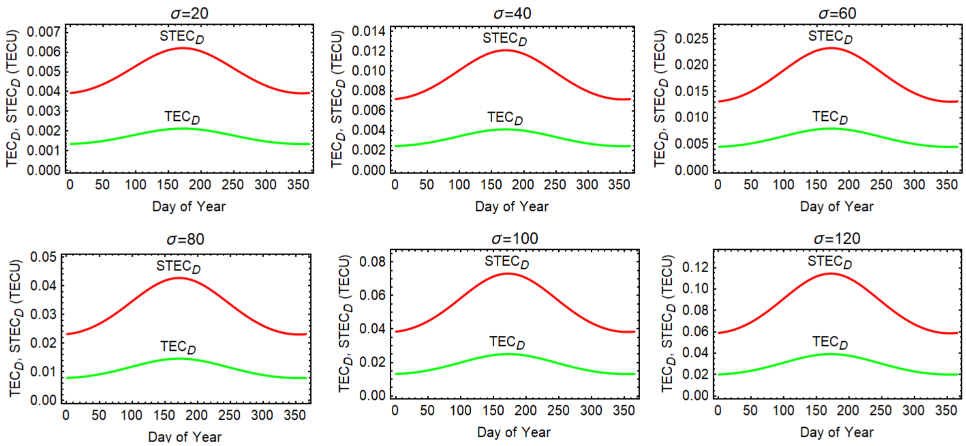

Fig. 3. Compared vertical and slant total electron content values in D-region over year for different σ values.

Conclusions

In this study, we present an analysis of the influence of variations in the intensity of the solar hydrogen Lyα radiation, arriving in the ionosphere on the D-region total electron content.

The obtained results show that the slant D-region total electron content has larger values than the corresponding vertical values. Furthermore, both quantities have maximal values during the summer solstice and increase with the sunspot number.

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References

Hofmann-Wellenhof, B., Lichtenegger, H., Wasle, E., 2008, Springer, Vienna.

Nina, A., Nico, G., Mitrović, S.T., Čadež, V.M., Milošević, I.R., Radovanović, M., Popović, L.Č., 2021, Remote Sens., 13(3), 483.

Seeber, G., 2003, Walter de Gruyter, Berlin, New York.

Thomson, N.R., 1993, J. Atmos. Terr. Phys., 55, 173.

Todorović Drakul, M., Čadež, V.M., Bajčetić, J., Popović, L.Č., Nina, A., Serb. Astron. J. 2016, 193, 11.

Wait, J. R., Spies, K. P., 1964, National Bureau of Standards, Boulder, CO.