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Influence of variations in the solar hydrogen Lyα radiation on the ionospheric D-region electron density during a year and solar cycle

A. Nina[1], **V.M. Čadež**[2], **L.Č. Popović**[2,3,4] **and M. Radovanović**[5,6]

[1] *Institute of Physics Belgrade, University of Belgrade, 11080 Belgrade, Serbia (E-mail: sandrast@ipb.ac.rs)*

[2] *Astronomical Observatory, 11060 Belgrade, Serbia*

[3] *Department of Astronomy, Faculty of mathematics, University of Belgrade, 11000 Belgrade, Serbia*

[4] *Faculty of Science, University of Banja Luka, 78000 Banja Luka, R. Srpska, Bosnia and Herzegovina*

[5] *Geographical Institute Jovan Cvijić SASA, 11000 Belgrade, Serbia*

[6] *South Ural State University, Institute of Sports, Tourism and Service, 454080 Chelyabinsk, Russia*

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Abstract. The hydrogen Lyα radiation emitted from the Sun is the main source of photo-ionization processes and, consequently, of the free electron production in the ionospheric D-region. Variations in the intensity of the incoming Lyα radiation affect changes in the electron density and they show up as periodic daily and seasonal changes, and changes during a solar cycle. The Quiet Ionospheric D-Region (QIonDR) model describes these periodic changes. In this study, we analyse how changes during a year and changes in the smoothed daily sunspot number (both processes affect the intensity of incoming radiation in the D-region) affect the electron density changes related to quiet conditions. The presented modelling is based on the results of the QIonDR model obtained for the part of Europe defined by the positions of the very low frequency (VLF) signal transmitters ICV (Sardinia, Italy) and DHO (Lower Saxony, Germany), and the AWESOME (Atmospheric Weather Electromagnetic System for Observation Modeling and Education) receiver position (Belgrade, Serbia) in application of the QIonDR model on real signals.

Key words: solar hydrogen Lyα line – ionospheric D-region – QIonDR model – VLF signals

1. Introduction

Study of the electron density dynamics in the ionosphere is of crucial importance for scientific research of many plasma parameters, and physical and chemical processes in this atmospheric layer, as well as for modelling of the ionospheric influence on different kinds of electromagnetic waves. Variations in the ionospheric electron density occur as a result of numerous permanent influences coming from the outer space (Basak & Chakrabarti, 2013; Chakraborty & Basak, 2020; Nina, 2022) and terrestrial layers (Kumar et al., 2017; Nina et al., 2020), and their influence can be both periodical and aperiodical.

The most important source of the free electron production in the ionosphere is the solar radiation. Depending on the wavelength of the photons of this radiation, the efficiency in the considered photo-ionization processes depends on the altitude. Thus, the most significant parts of the spectrum that ionize the ionospheric D-region are the Lyα (121.6 nm) during quiet conditions and X-radiation generated by solar X-ray flares.

In this paper we analyse periodical variations of the ionospheric D-region electron density induced by local variations in the intensity of the solar hydrogen Lyα radiation at the considered area. We perform calculations based on Wait's model (Wait & Spies, 1964) by considering the ionosphere as a horizontally uniform medium with the electron density increasing exponentially with height according to an expression described by two independent, the so-cold Wait's, parameters: the "sharpness", and the signal reflection height.

There are several procedures for the quiet ionosphere parameters determination. Generally, they are based on the broad-band detection of radio atmospherics in periods of lightning activities (Han et al., 2011; Ammar & Ghalila, 2020) and detection of the narrow-band very low frequency (VLF) signals (Thomson, 1993; McRae & Thomson, 2000; Thomson et al., 2011; Nina et al., 2021). In this paper, we analyse variations of the D-region electron density N depending on the smoothed daily sunspot number, σ, and on its variations in time (t) and on the day of year (DOY). We apply the Quiet ionospheric D-region (QIonDR) model (Nina et al., 2021) that provides dependencies of Wait's parameters on σ and DOY for the part of Europe defined by the positions of the VLF signal transmitters ICV (Sardinia, Italy) and DHO (Lower Saxony, Germany), and the AWESOME (Atmospheric Weather Electromagnetic System for Observation Modeling and Education) receiver (Belgrade, Serbia) which are used to develop this model. The mentioned dependences of these parameters in the QIonDR model were obtained by fitting relevant values calculated in processing of observational data during perturbations caused by 9 solar X-ray flares that occurred during all four seasons in the midday periods from 2009 to 2016. The application of the obtained functions enables the modelling of White's parameters and, consequently, the electron density in the D-region during quiet midday conditions without observational data only by DOY and σ (it can be obtained based on the appropriate data available on the Internet) entering into the calculations for the considered day.

2. Modelling

The electron density modelling is based on Wait's model of the ionosphere, which involves a horizontally uniform ionosphere described by two independent Wait's parameters, the "sharpness" (β) and the signal reflection height (H') and the expression from Thomson (1993):

$$N(\sigma,\chi,h) = 1.43 \cdot 10^{13} e^{-\beta(\sigma,\chi)H'(\sigma,\chi)} e^{[\beta(\sigma,\chi)-0.15]h}, \quad (1)$$

where N, β and H' are given in m^{-3}, km^{-1} and km, respectively.

The dependencies of Wait's parameters on σ and the seasonal parameter χ are calculated using the QIonDR model (Nina et al., 2021):

$$\beta_0 = 0.2635 + 0.002573 \cdot \sigma - 9.024 \cdot 10^{-6} \sigma^2 + 0.005351 \cdot \cos(2\pi(\chi - 0.4712)), \quad (2)$$

and

$$H'_0 = 74.74 - 0.02984 \cdot \sigma + 0.5705 \cdot \cos(2\pi(\chi - 0.4712) + \pi). \quad (3)$$

These equations were obtained in the aforementioned study based on observational data of the DHO and ICV signals emitted in Germany (53.08 N, 7.61E) and Italy (40.92 N, 9.73 E), respectively, and recorded in Serbia (44.8 N, 20.4 E). For this reason, they are relevant for the area between these transmitters and receivers, i.e. approximately for the D-region above Central Europe.

Here, we point out that the uncertainties of the mentioned procedure are caused both by the approximations related to the White model of the ionosphere and by the approximations applied in the QIonDR model. These approximations primarily refer to considering the D-region as a horizontally uniform medium and the electron density distribution as an exponential function of height. In addition, the functional dependences of Wait's parameters on DOY and σ in the QIonDR model were obtained by fitting the relevant values of observational data for 9 analysed cases that met the analysis criteria. In specific cases, deviations of the relevant values from those given by these fitted functions are expected due to the constant influence of a large number of events and processes on the ionosphere.

The absolute variations of electron density due to changes in the observed σ and DOY are calculated based on the expressions:

$$\frac{\Delta N(\sigma(i),\chi(j),h)}{\Delta\sigma} = \frac{1}{2}\left(N(\sigma(i+1),\chi,h) - N(\sigma(i-1),\chi,h)\right), \quad (4)$$

and

$$\frac{\Delta N(\sigma(i),\chi(j),h)}{\Delta d} = \frac{1}{2}\left(N(\sigma(i),\chi(j+1),h) - N(\sigma(i),\chi(j-1),h)\right) \quad (5)$$

where the i-th value of $\sigma(i)$ is calculated using the expression $\sigma(i) = 19 + i$ ($i = 1, 2, 3, ..., 101$), and the value of $\chi(j) = j/\mathrm{NDY}$ (j=1,2,3,...,NDY, where NDY is the number of days in a year).

In this paper, the relative changes of the electron density with σ and DOY are analysed. They are calculated by dividing Eqs. (4) and (5) with the corresponding value of the electron density, respectively.

3. Results and discussion

In this Section, we present the results of modelling the electron density changes with σ (Section 3.1) and with DOY (Section 3.2). In both cases, we observe absolute and relative changes in the electron density at heights H= 60 km, 70 km, 80 km and 90 km for all combinations of DOY and σ ranging between 20 to 120.

3.1. Solar cycle variations

The electron density changes during a year and solar cycle. Consequently, variations in the solar hydrogen Lyα radiation do not have the same effect on the D-region characteristics at different periods. To examine how changes in σ affect changes in electron density under different conditions, we study the dependencies of the derivatives $\frac{\Delta N}{\Delta \sigma}$ versus DOY and σ. The results of this modelling, based on the expressions given in Section 2, are shown in Fig. 1. Based on the obtained panels we can conclude the following:

- The tendencies of the absolute changes of N are the same for all D-region heights.

- The intensity of these changes increases with altitude. For observed heights that differ by 10 km, the values on the scales differ by more than one order of magnitude.

  For small values of σ at 70 km, the obtained values of $\frac{\Delta N}{\Delta \sigma}$ are below 10^{-6} m^{-3}. Because of approximations taken in the QIonDR model, these values can be considered approximately equal to 0. By decreasing the height, the maximum values of σ to which this approximation is applied increase (the exact value depends on DOY).

- Changes in the electron density for the same DOY increase with σ.

- The most pronounced changes in $\frac{\Delta N}{\Delta \sigma}$ for all values of σ occur in the period around the summer solstice.

Bearing in mind that the electron density changes with height, we analyse its relative changes with sigma to determine the local significance of changes in emitted solar hydrogen Lyα radiation. For this reason, we apply the procedure

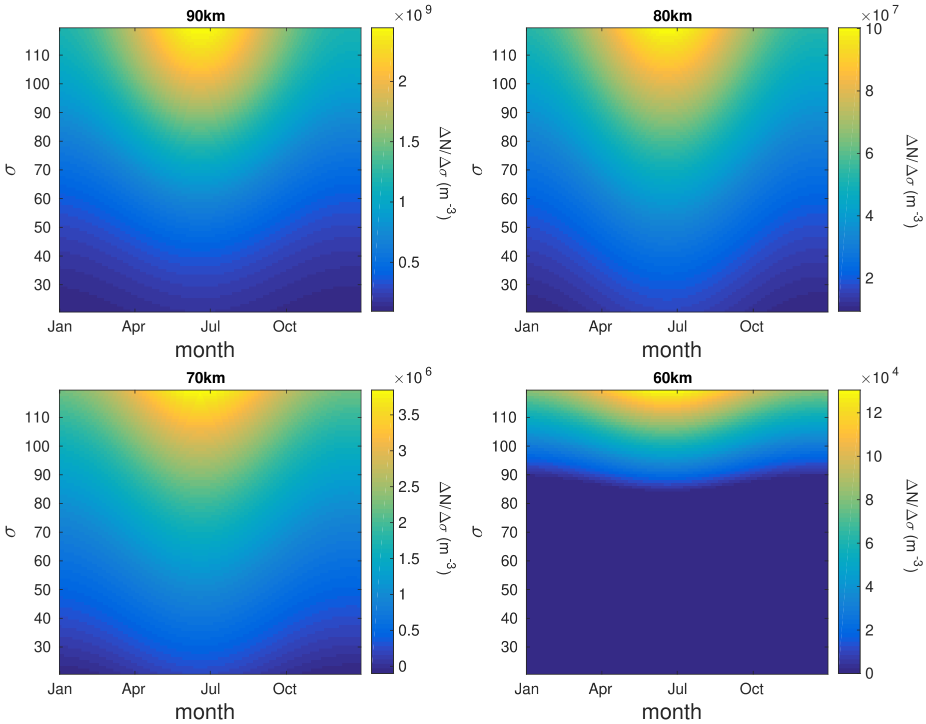

Figure 1. Ratio of variations ΔN and $\Delta\sigma$ $\frac{\Delta N}{\Delta\sigma}$, versus DOY and σ at heights h= 60, 70, 80 and 90 km.

shown in the previous case to determine the dependencies $\frac{1}{\Delta\sigma}\frac{\Delta N}{N}$. Based on the obtained results visualized in Fig. 2, the following characteristics of $\frac{1}{\Delta\sigma}\frac{\Delta N}{N}$ changes can be observed:

– The maximum values of $\frac{1}{\Delta\sigma}\frac{\Delta N}{N}$ at all D-region heights are within one order of magnitude for the observed values of σ, and they increase with height;

– The maximum considered relative changes occur in the summer solstice period.

– The maximum relative changes of N with the smoothed daily sunspot number occur at smaller values of σ with increasing height.

– As a consequence of the small values of $\frac{\Delta N}{\Delta\sigma}$ in the lower part of the D-region for lower values of σ, it can be concluded that the relative changes in these parameters are negligible.

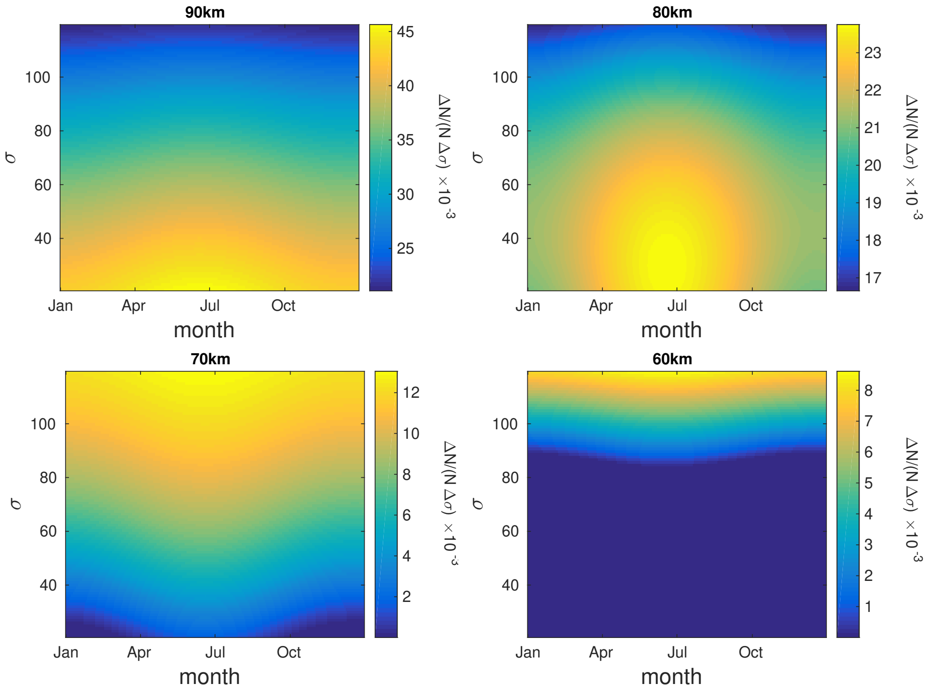

Figure 2. Dependencies of the relative changes in the electron density with the changes of the smoothed daily sunspot number, $\frac{\Delta N}{N \Delta \sigma}$, on DOY and σ at h = 60, 70, 80 and 90 km.

3.2. Seasonal variations

The analysis of the electron density absolute and relative changes with DOY is shown in a similar way as in the previous case.

Based on the obtained 3D dependencies of the electron density absolute changes shown in Fig. 3, the following conclusions can be drawn:

– The intensity of these changes increases with the height, and their maxima at the lower and upper boundaries of the D-region differ by about 4 orders of magnitude.

– From the winter to summer solstice $\frac{\Delta N}{\Delta d}$ is positive, while going from a summer to a winter solstice, this parameter is negative. Changes in the electron density with DOY are most pronounced during equinoxes.

– The influence of σ on $\frac{\Delta N(\sigma(i),\chi(j),h)}{\Delta d}$ increases with height.

The relative changes of the electron density (presented in Fig. 4) show the following characteristics:

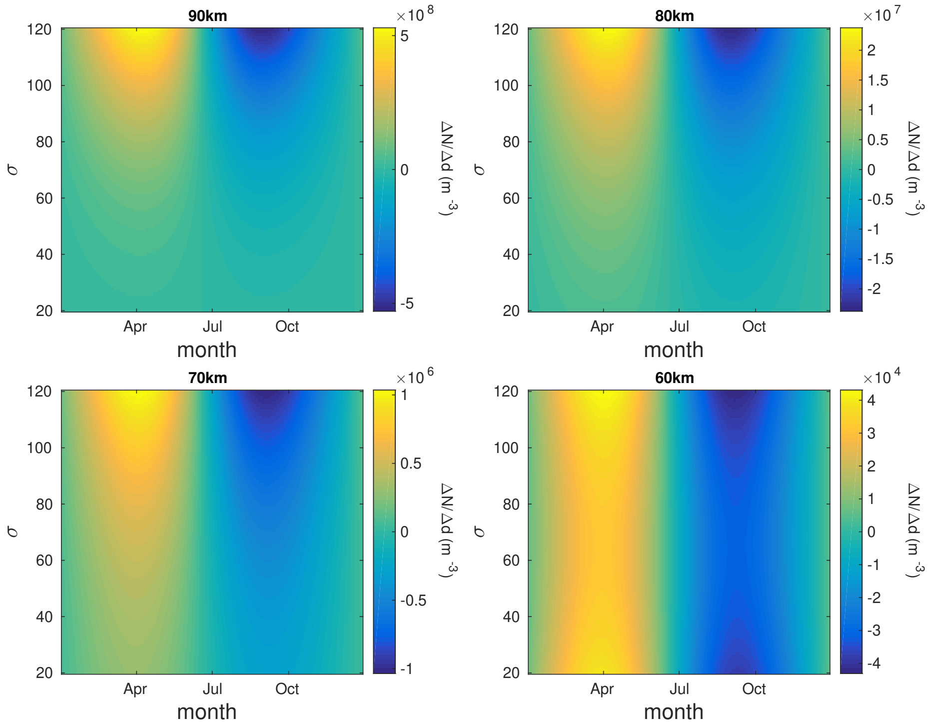

Figure 3. Dependencies of the absolute changes in the electron density with the day $\frac{\Delta N}{\Delta d}$, versus DOY and σ.

- The values of $\frac{1}{\Delta d}\frac{\Delta N}{N}$ for the same σ and for the same day are within one order of magnitude in the entire D-region.
- The influence of σ on the observed changes is not expressed. It is most pronounced during the summer and winter solstices.
- As in the case of absolute changes, $\frac{1}{\Delta d}\frac{\Delta N}{N}$ is positive in the period between the winter solstice and summer solstice, while going from the summer to winter solstice it is negative.

4. Conclusions

In this paper, the absolute and relative changes of the mid-day D-region electron density during a year and a solar cycle were analysed. The analyses are based on modelling the undisturbed ionospheric D-region by the QIonDR model. The obtained results show the following:

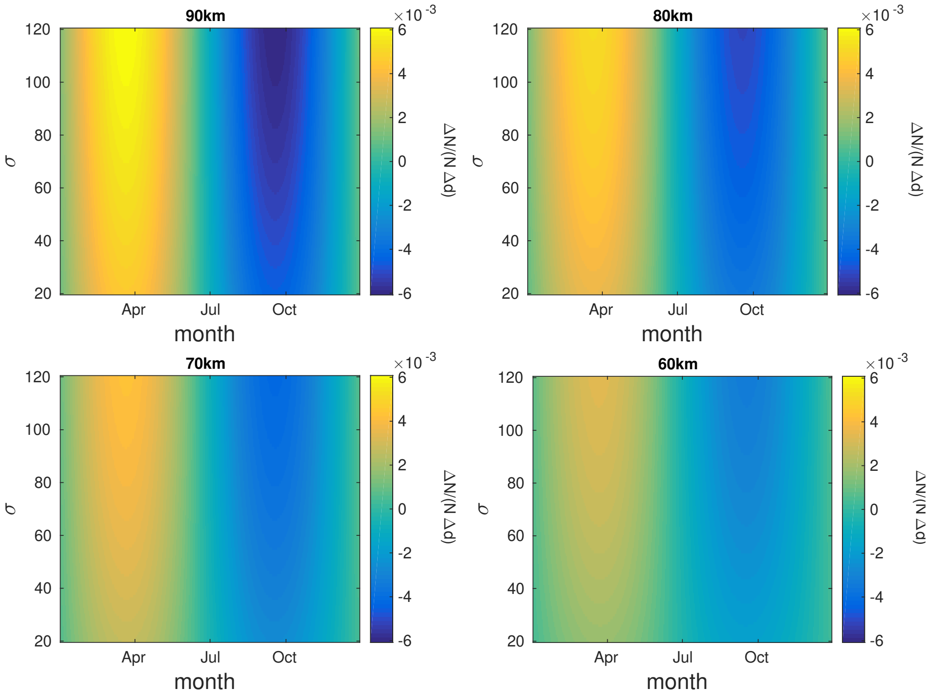

Figure 4. Dependencies of the relative changes in the electron density with the day $\frac{\Delta N}{N\Delta d}$, versus DOY and σ.

– Both, the absolute and relative changes in the electron density with the smoothed daily sunspot number and with the day of year increase with altitude.

– The maximum absolute changes at the upper and lower limits differ by about four orders of magnitude, while the corresponding maximum relative changes differ by about 2 times.

– Due to the small values of changes in the electron density with the smoothed daily sunspot number at the lower altitudes of the D-region, it can be considered that they are negligible for smaller values of the smoothed daily sunspot number.

– The maximum values of the observed changes in the electron density with the smoothed daily sunspot number are in the period of the solstices, while those changes with the day of year are most intense in the periods of equinoxes.

- The resulting assessment of the influence of the smoothed daily sunspot number on the observed changes in the electron density based on the QIonDR model has more complex characteristics than in the case of seasonal changes:
  - The absolute changes in the electron density with the smoothed daily sunspot number increase with this number at all altitudes throughout a year.
  - The maximum relative changes of the electron density with the smoothed daily sunspot number occur during the period of the summer solstice. The smoothed daily sunspot number corresponding to these maximum changes decrease with the D-region heights.
  - At higher altitudes, the absolute changes in the electron density with days at higher altitudes increase with the smoothed daily sunspot number.
  - The relative changes in the electron density with days increase with the smoothed daily sunspot number at all altitudes.

Finally, it should be emphasized that it is not possible to check the obtained dependencies on the basis of other models. Namely, some of the other existing models do not give dependences on both observed parameters, while some expressions use dependences on the Zürich sunspot number, which has been replaced by the international sunspot numbers since 1980. Therefore, it is necessary to verify the obtained conclusions in the future.

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References

Ammar, A. & Ghalila, H., Estimation of nighttime ionospheric D-region parameters using tweek atmospherics observed for the first time in the North African region. 2020, *Advances in Space Research*, **66**, 2528, DOI: 10.1016/j.asr.2020.08.025

Basak, T. & Chakrabarti, S. K., Effective recombination coefficient and solar zenith angle effects on low-latitude D-region ionosphere evaluated from VLF signal amplitude and its time delay during X-ray solar flares. 2013, *Astrophysics and Space Science*, **348**, 315, DOI: 10.1007/s10509-013-1597-9

Chakraborty, S. & Basak, T., Numerical analysis of electron density and response time delay during solar flares in mid-latitudinal lower ionosphere. 2020, *Astrophysics and Space Science*, **365**, 184, DOI: 10.1007/s10509-020-03903-5

Han, F., Cummer, S. A., Li, J., & Lu, G., Daytime ionospheric D region sharpness derived from VLF radio atmospherics. 2011, *Journal of Geophysical Research (Space Physics)*, **116**, 5314, DOI: 10.1029/2010JA016299

Kumar, S., NaitAmor, S., Chanrion, O., & Neubert, T., Perturbations to the lower ionosphere by tropical cyclone Evan in the South Pacific Region. 2017, *Journal of Geophysical Research: Space Physics*, **122**, 8720, DOI: 10.1002/2017JA024023

McRae, W. M. & Thomson, N. R., VLF phase and amplitude: daytime ionospheric parameters. 2000, *Journal of Atmospheric and Solar-Terrestrial Physics*, **62**, 609, DOI: 10.1016/S1364-6826(00)00027-4

Nina, A., Modelling of the Electron Density and Total Electron Content in the Quiet and Solar X-ray Flare Perturbed Ionospheric D-Region Based on Remote Sensing by VLF/LF Signals. 2022, *Remote Sensing*, **14**, DOI: 10.3390/rs14010054

Nina, A., Nico, G., Mitrović, S. T., et al., Quiet Ionospheric D-Region (QIonDR) Model Based on VLF/LF Observations. 2021, *Remote Sensing*, **13**, DOI: 10.3390/rs13030483

Nina, A., Pulinets, S., Biagi, P., et al., Variation in natural short-period ionospheric noise, and acoustic and gravity waves revealed by the amplitude analysis of a VLF radio signal on the occasion of the Kraljevo earthquake (Mw = 5.4). 2020, *Science of the Total Environment*, **710**, 136406, DOI: 10.1016/j.scitotenv.2019.136406

Thomson, N. R., Experimental daytime VLF ionospheric parameters. 1993, *Journal of Atmospheric and Terrestrial Physics*, **55**, 173, DOI: 10.1016/0021-9169(93)90122-F

Thomson, N. R., Rodger, C. J., & Clilverd, M. A., Daytime D region parameters from long-path VLF phase and amplitude. 2011, *Journal of Geophysical Research (Space Physics)*, **116**, 11305, DOI: 10.1029/2011JA016910

Wait, J. R. & Spies, K. P. 1964, *Characteristics of the Earth-ionosphere waveguide for VLF radio waves,* , NBS Technical Note, CO