URSI GASS 2023, Sapporo, Japan, 19 – 26 August 2023

A Neural network model of Electron density in Earth's Topside ionosphere (NET)

Artem Smirnov*[1,2], Yuri Shprits[1,2,3], Fabricio Prol[4], Hermann Lühr[1], Max Berrendorf[5], Irina Zhelavskaya[1], Chao Xiong[6]

(1) Helmholtz Centre Potsdam – GFZ German Research Centre for Geosciences, Potsdam, Germany
(2) Institute of Physics and Astronomy, University of Potsdam, Potsdam, Germany
(3) Department of Earth, Planetary and Space Sciences, University of California Los Angeles, CA, USA
(4) Department of Navigation and Positioning, Finnish Geospatial Research Institute (FGI), National Land Survey of Finland (NLS), Kirkkonummi, Finland
(5) Institute of Informatics, Ludwig-Maximiliand-University of Munich, Munich, Germany
(6) Department of Space Physics, College of Electronic Information, Wuhan University, Wuhan, China
* email: asmirnov@gfz-potsdam.de

Abstract

The ionosphere is an ionized part of the upper atmosphere, where the number of free electrons is large enough to affect the propagation of radio signals, including those of the GNSS systems. The knowledge of electron density values in the ionosphere is crucial for both industrial and scientific applications. Here, we develop a novel empirical model of electron density in the topside ionosphere using the radio occultation profiles collected by the CHAMP, GRACE, and COSMIC missions. We assume a linear decay of scale height with altitude and model four parameters, namely the F2-peak density and height (NmF2 and hmF2) and the slope and intercept of the linear scale height decay (dHs/dh and H0). The resulting model (NET) is based on feedforward neural networks. The model inputs include the the geographic and geomagnetic position, the solar flux and geomagnetic indices. The resulting density reconstructions are validated on more than a hundred million in-situ measurements from CHAMP, CNOFS and Swarm satellites, as well as on the GRACE/KBR data, and the developed NET model is compared to several topside options of the International Reference Ionosphere (IRI) model. The NET model yields highly accurate reconstructions of the topside ionosphere and gives unbiased predictions for different locations, seasons, and solar activity conditions.

1 Introduction

The Earth's ionosphere is a region of paramount importance for a variety of scientific and industrial applications. In particular, the ionosphere contains free electrons that can interfere with propagation of radio signals, including those of the GNSS systems, and is considered to be one of the most significant sources of error in positioning (up to ~100 m for single-frequency positioning). The ionospheric delays are proportional to electron density integrated along the ray path, and therefore it is crucial to have highly accurate models of ionospheric electron density. In particular, the part of the ionosphere located above the F2-layer peak, known as the topside ionosphere, contains up to 80% of the total electron content (TEC), and is therefore especially important for GNSS applications [1].

A variety of ionospheric electron density models have been developed over the last five decades. The models initially were targeted to reproduce electron densities at the F2-peak and the bottomside and were based on the ground-based ionosonde observations. Later on, the empirical models were extended into the topside using satellite data from the topside sounder missions as well as incoherent scatter radar observations. The empirical models, including the International Reference Ionosphere (IRI) also use in-situ observations of electron density in the topside ionosphere. It should be noted, however, that the data distribution in the topside is highly non-uniform, both with respect to the solar cycle coverage and in altitude. This makes the topside modeling a challenging task, and the existing climatological models exhibit substantial discrepancies from observations, which are evident both from the comparisons to independent in-situ data and TEC magnitudes.

Over the last two decades, the ionosphere has become increasingly data-rich, with billions of data points provided by the GNSS radio occultation (RO) technique. The RO data were shown to agree well with the in-situ data and can therefore be used as an important data source for empirical modeling [5]. One of the most efficient ways to utilize such vast amounts of data for modeling is by using machine learning techniques. Here, we present a machine learning model of electron density in the topside ionosphere, which was trained based on 19 years of RO observations and tested on independent in-situ observations. The developed Neural network model of Electron density in the Topside ionosphere (NET) shows an excellent agreement with observations and gives unbiased and highly accurate electron density predictions for a variety of solar and geomagnetic conditions.

2 Model formulation

Electron density in the topside ionosphere can be well approximated by a Chapman function with a linear decay of scale height with altitude, using the following equation:

$$\begin{cases} N_e(h) = \mathrm{NmF2} \cdot \exp\left(0.5(1 - z - \exp(-z))\right), \\ \qquad z = \frac{h - \mathrm{hmF2}}{H_s(h)}, \\ H_s(h) = \frac{\mathrm{dHs}}{\mathrm{dh}}(h - \mathrm{hmF2}) + \mathrm{H}_0, \end{cases} \quad (1)$$

This approximation yields four parameters, namely the peak density of the F2-layer (NmF2), the altitude of the peak (hmF2), and 2 parameters of the scale height decay with altitude (slope H0 and intercept dHs/dh), which are modeled using feedforward neural networks. We model each of the parameters separately and then combine them using the Equation (1) to get electron density predictions (the details of the model development are given in [3]). As inputs to the model, we use geographic and magnetic coordinates, magnetic local time, day of year, solar index P10.7 which represents a smooth version of the 10.7 cm solar radio flux F10.7, and geomagnetic indices Kp and SYM-H.

3 Model testing on COSMIC data

Figure 1 shows a comparison of NET model predictions with Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) electron densities on the test set. It can be seen that the model yields unbiased electron density estimates, as the 2D histogram is centered around the one-to-one correspondence line. One useful metric of the model performance is the ratio between the model predictions and observations. In this study, we take the values of ratio >1 in linear scale, and take the inverted values for ratios <1 (see also [3]). Then, the cumulative distribution of the ratios can reveal what percent of the model predictions lie within a given factor from the data. In Figure 1(b) we show that the NET predictions are within a factor of 2 from the data >96% of the time. This demonstrates that the model yields highly accurate representation of the radio occultation observations. It should be noted that the data showed in Figure 1 were not used for the model training and therefore represent the model performance on the unseen events.

Figure 1 shows data combined across all seasons, locations and altitudes, and therefore it is important to also evaluate the model locally for specific seasonal and solar activity conditions. Smirnov et al. [3] performed the spatial binning of the NET predictions for different seasons in magnetic latitude and local time, and demonstrated that the model gave unbiased predictions for all seasons and locations.

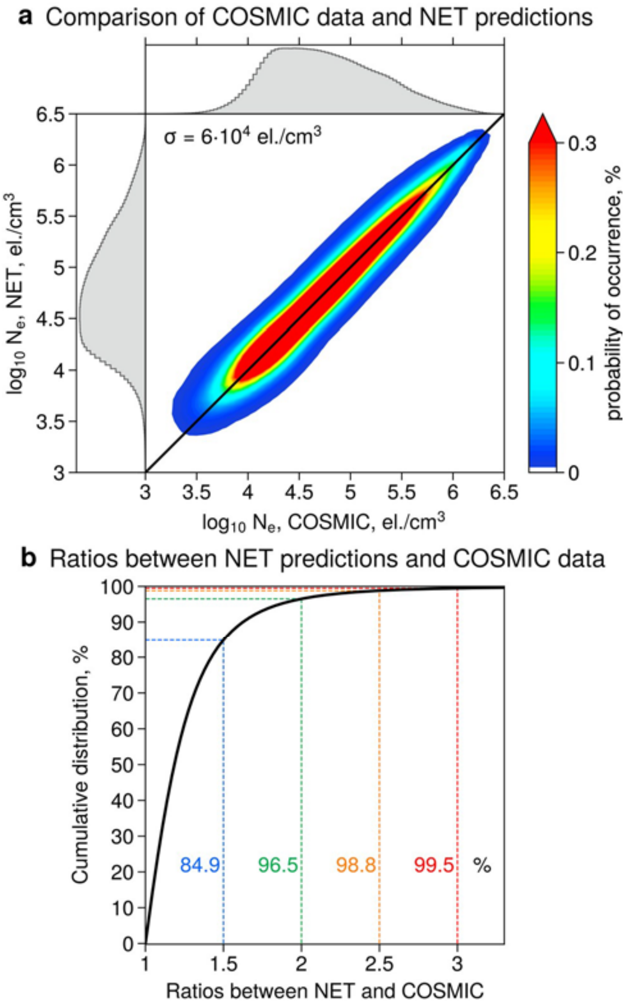


Figure 1. (a) Comparison of NET model predictions and COSMIC electron density observations from the test set (not used in model training). The black line shows the one-to-one correspondence, and it can be seen that the 2D histogram is centered along this line, which shows that the NET model gives unbiased predictions on the COSMIC data. (b) Cumulative distribution of the ratios between NET predictions and COSMIC data. [3]

Another useful way to evaluate the model performance is to analyze the model bias at different altitudes. In particular, in the topside it is convenient to perform such analysis using height relative to the F2-peak altitude. In Figure 2, we show the vertical percentage bias of the NET and IRI-2016 models. It can be seen that the NET model residuals generally remain within a 5% range, while the IRI-2016 model tends to underestimate the NmF2 and can overestimate electron densities above the F2-layer peak. Smirnov et al. [3] showed that the most significant residuals of the IRI-2016 model with the NeQuick topside come from the region of 100-200 km above the F2-layer peak. This can be attributed to the topside formulation used in the NeQuick topside shape option of the IRI. In particular, the NeQuick model uses a fixed value of the scale height gradient, which leads to vertical residual shape shown in Figure 2, while in the NET model the gradient of scale height is modeled as a function of location for different solar and geomagnetic conditions, which makes this parametrization very flexible and results in mostly unbiased electron density profiles.

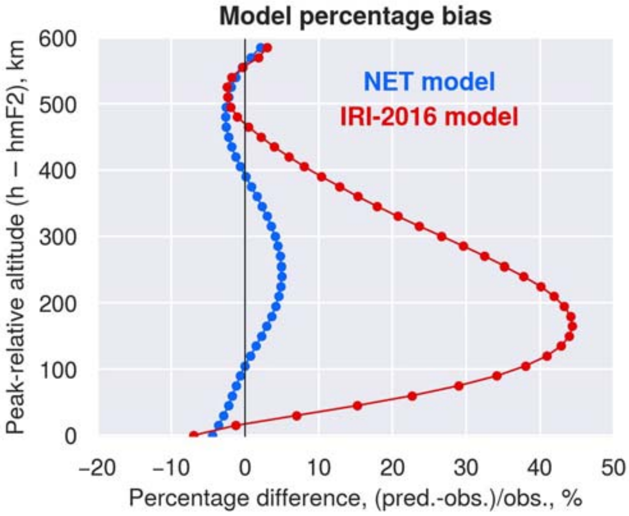


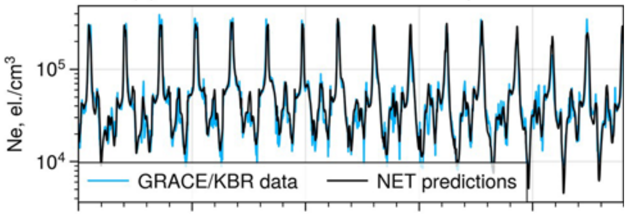
Figure 2. Model residuals (in %) for the NET and IRI-2016 models, binned by altitude relative to hmF2. [3]

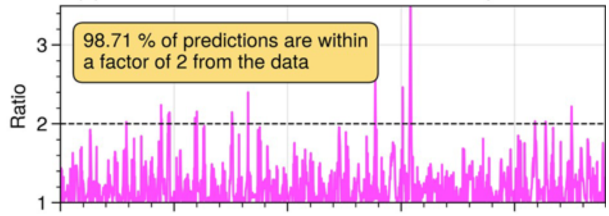
4 Model testing on independent data

The NET model was trained on COSMIC data, and therefore it is also necessary to evaluate the model performance using independent in-situ observations. In this study, we use the Gravity Recovery And Climate Experiment (GRACE) – K-band Ranging (KBR) electron density observations, which were calibrated by the incoherent scatter radar data and represent a “golden standard” data set of the topside ionosphere spanning over >10 years [5].

Figure 3 shows a comparison between GRACE-KBR observations and NET predictions for one of the days corresponding to the test interval. It can be seen that the model reproduces the GRACE measurements very well, both in the equatorial ionization anomaly (EIA) region that corresponds to high electron densities and in polar regions that generally have smaller electron density values. In Figure 3(b), we demonstrate the ratios between the model and observations. It is of note that over 98% of time, the predictions lie within a factor of 2 from the data, which shows the capacity of the model to not only reproduce the radio occultation data, but also in-situ observations from fully independent missions.

While in this paper we only demonstrate a comparison of NET predictions to observations for 1 day, Smirnov et al. [3] give a much more detailed model validation examples, by using the entire GRACE-KBR data set and also Challenging Minisatellite Payload (CHAMP) and Communications/Navigation Outage Forecast System (C/NOFS) data. Their study demonstrates that on all of these data sets, NET predictions are consistently within a factor of 2 from the data 90% of the time [3].


(a) GRACE observations and NET predictions


(b) Ratios between GRACE data and NET predictions

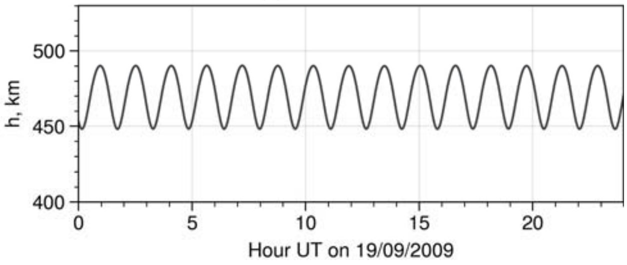

(c) GRACE altitude

Figure 3. (a) In-situ GRACE observations and NET predictions on 19 September 2009 (note that this day was not used for model training and belongs to the test interval), (b) Rations between the model predictions and the data, (c) GRACE altitude.

5 Conclusions and future directions

A novel empirical model of the topside ionosphere (NET) has recently been developed [3]. The model is based on the Chapman functions with a linear scale height decay. The model uses the geographic and magnetic coordinates, magnetic local time, and a combination of the solar and geomagnetic indices to predict 4 parameters of the linear alpha-Chapman equation and was trained and tested on 19 years of radio occultation data, as well as on additional in-situ measurements from GRACE, CHAMP and C/NOFS missions. The model yields highly accurate electron density reconstructions for a variety of solar and geomagnetic conditions and can have wide applications in ionospheric research.

The model is currently based on radio occultation data and produces high-quality density predictions up to ~1000 km in altitude. The model can be extended in altitude by adding the topside sounder data, which would allow density reconstructions up to altitudes of 2000-3000 km. Furthermore, due to the fact that most of the conditions during the last two solar cycles corresponded to geomagnetically quiet times, the model inputs can be resampled to target specifically the geomagnetically active conditions. Furthermore, the model can be connected to plasmaspheric altitudes by using methodology described in [2] and can therefore be used to generate TEC maps.

The current version of the NET model is publicly available [4], and the newly updated versions will also be fully accessible by the community. One of the current plans is to make the model operational in real time and introduce a website interface to perform the model runs on request.

Acknowledgements

Artem Smirnov acknowledges support from the International Space Science Institute (ISSI - Bern, Switzerland) through the ISSI team on "Imaging the Invisible: Unveiling the Global Structure of the Earth's Dynamic Magnetosphere". This study is supported by the Helmholtz Pilot Projects Information & Data Science II, MAchine learning based Plasma density model project (MAP) – ZT-I-0022.

References

1 Bilitza, D. (2009). Evaluation of the IRI-2007 model options for the topside electron density. *Advances in space research*, *44*(6), 701-706.

2 Prol, F. S., Smirnov, A. G., Hoque, M. M., & Shprits, Y. Y. (2022). Combined model of topside ionosphere and plasmasphere derived from radio-occultation and Van Allen Probes data. *Scientific reports*, *12*(1), 1-11.

3 Smirnov, A., Shprits, Y., Prol, F., Lühr, H., Berrendorf, M., Zhelavskaya, I., & Xiong, C. (2023). A novel neural network model of Earth's topside ionosphere. *Scientific Reports*, *13*(1), 1303, doi: 10.1038/s41598-023-28034-z

4 Smirnov, Artem; Shprits, Yuri; Prol, Fabricio; Lühr, Hermann; Berrendorf, Max; Zhelavskaya, Irina; Xiong, Chao (2023): Model files for the Neural network-based model of Electron density in the Topside ionosphere (NET). V. 1.0. GFZ Data Services. https://doi.org/10.5880/GFZ.2.7.2023.001

5 Smirnov, A., Shprits, Y., Zhelavskaya, I., Lühr, H., Xiong, C., Goss, A., ... & Szabó-Roberts, M. (2021). Intercalibration of the plasma density measurements in Earth's topside ionosphere. *Journal of Geophysical Research: Space Physics*, *126*(10), e2021JA029334.