Natural Resources Canada | Ressources naturelles Canada

GEOMATICS CANADA
OPEN FILE 59

An investigation on the GNSS ionospheric mapping-functions uncertainties using NeQuick model

R. Ghoddousi-Fard

2020

Canada

GEOMATICS CANADA
OPEN FILE 59

An investigation on the GNSS ionospheric mapping-functions uncertainties using NeQuick model

R. Ghoddousi-Fard

[1]Canadian Geodetic Survey, 588 Booth Street, Ottawa, Ontario K1A 0Y7

2020

Permanent link: https://doi.org/10.4095/326084

This publication is available for free download through GEOSCAN (https://geoscan.nrcan.gc.ca/).

Recommended citation
Ghoddousi-Fard, R., 2020. An investigation on the GNSS ionospheric mapping-functions uncertainties using NeQuick model; Geomatics Canada, Open File 59, 11 p. https://doi.org/10.4095/326084

Publications in this series have not been edited; they are released as submitted by the author.

An investigation on the GNSS ionospheric mapping functions uncertainties using NeQuick model

Reza Ghoddousi-Fard

Abstract

Commonly used two-dimensional ionospheric models for GNSS positioning applications, including Total Electron Content (TEC) maps, require a mapping function (obliquity factor) which is used for conversion between vertical and slant TEC at ionospheric pierce points. In this paper, NeQuick, a three-dimensional semi-empirical model, is used to simulate the level of uncertainties that one may expect from more simplified approaches. In order to evaluate the performance of mapping functions on GNSS vertical TEC estimation, coinciding pierce points from mixed stations and receivers from stations over North America are analyzed. A fit to the NeQuick derived mapping function values resulted in an empirical mapping function which performed slightly better than commonly used mapping functions during the studied periods and locations.

Introduction

Due to computational load and inefficiency of three-dimensional ionospheric models to predict the effects of space weather events, most GNSS processing algorithms are still relying on two-dimensional ionospheric models where a conversion of vertical Total Electron Content (TEC) values to the satellite to receiver line of sight is required.

NeQuick is a three-dimensional, time dependent ionospheric electron density model developed at the Aeronomy and Radio Propagation Laboratory of the Abdus Salam International Centre for Theoretical Physics (ICTP), Italy and at the Institute for Geophysics, Astrophysics and Meteorology of the University of Graz, Austria [Hochegger et al., 2000; Nava et al., 2008]. The model allows one to calculate TEC along any ray-path by means of integration of electron concentration. In the NeQuick model, the ionosphere is vertically divided into two parts: below and above the peak of F2 region. NeQuick model version 2.0.2 used in this study is improved over version 1 both in bottom-side and topside formulations [Nava et al., 2008].

Input parameters to the NeQuick model are coordinates of both ends of the ray path, year, month, time of day and an ionization parameter, which can be either a twelve-month running mean sunspot number (R12) or 10.7 cm wavelength solar radio flux (F10.7). In order to minimize the model error, the ionization parameter can reflect daily solar activity and hence it is a parameter that can be optimized to improve the model performance (see e.g. Memarzadeh, 2009).

Schüler and Oladipo [2013] reported a minor improvement in single-frequency single-site TEC retrieval precision by using the NeQuick based mapping function. Their results were based on comparing estimated vertical TEC (VTEC) using a commonly used mapping function and those derived from NeQuick with the IGS global TEC map as a reference value.

In an effort to quantify the uncertainties caused by ionospheric mapping functions used in GNSS processing for conversion between slant and vertical TEC, the differences between commonly used geometric mapping functions and the one derived from NeQuick are studied at different nominal solar conditions. In this paper, the difference caused by mapping function in the observation domain is simulated at different elevation angles, ionization levels and locations. The mapping function resulting from a least square fit to NeQuick values at different azimuths together with commonly used geometric mapping functions are evaluated by estimation of VTEC at coinciding ionospheric pierce points (IPP) from mixed receivers and stations over North America.

Geometric mapping functions vs. NeQuick ray-tracer

In order to simulate the difference caused by mapping functions in GNSS ionospheric slant delay, three locations at different geodetic latitudes (0, 50 and 80) at longitude of -90 as well as three levels of ionization by means of three different values of monthly smoothed sunspot numbers (5, 70 and 150) are chosen. Other required parameters for the NeQuick model are selected as the year of 2013 and month of September. At every hour of the day the ratio of slant to vertical TEC values (at locations corresponding to a shell height of 450 km) are calculated at elevation angles of 5, 10, 20, 30, 40, 50, 60, 70 and 80 degrees and are hereafter referred to as the NeQuick mapping function (m_{NeQ}).

The simplest yet most commonly used ionospheric mapping function is based on the single layer model on a spherical earth. This mapping function is hereafter referred to as the Standard mapping function and can be written as:

$$m_{std} = \frac{1}{cos\left(asin\left(\frac{R}{R+H} \cdot \sin(z)\right)\right)} \quad (1)$$

where *H* is the ionospheric shell height and *Z* is the zenith angle at the station on a spherical Earth with radius *R*.

Schaer [1999] proposed a modified single layer mapping function using a reduced zenith angle i.e.:

$$m_{mod} = \frac{1}{cos\left(asin\left(\frac{R}{R+H_{opt}} \cdot \sin(\alpha.z)\right)\right)} \quad (2)$$

The best fit of equation (2) to the Jet Propulsion Laboratory's extended slab model [Coster et al., 1992] was achieved at $H_{opt} = 506.7km$ and $\alpha = 0.9782$ [Beutler et al., 2007] and hereafter is referred to as the Modified mapping function. This mapping function is also being widely used. One may refer to Ghoddousi-Fard and Lahaye (2016) to see more details on commonly used mapping functions.

The difference in slant ionospheric delay as a result of the difference of a geometric mapping function from the NeQuick based mapping function on GPS L1 frequency can be derived from:

$$d = I \times (m_{NeQ} - m_{std[mod]}) \times VTEC_{NeQ} \tag{3}$$

where $VTEC_{NeQ}$ is the VTEC from NeQuick model in TECU, I is the conversion factor of TECU to cm in GPS L1 frequency (~16.2), m_{NeQ} is the NeQuick based mapping function, $m_{std[mod]}$ is either of the Standard or Modified mapping functions defined in equations (1) and (2) and *d* is the slant delay difference in cm.

Figure 1 shows as an example, azimuth dependent difference in slant delay caused by mapping function over 24 hours at longitude of -90 on the geodetic equator at 10 degrees elevation angle with a moderate ionization level (R12) of 70. It can be seen that differences can reach up to meter level at some azimuths and times. Daily mean differences between the two geometric mapping functions from NeQuick at all studied elevation angles and ionization levels, are plotted in figures 2 and 3.

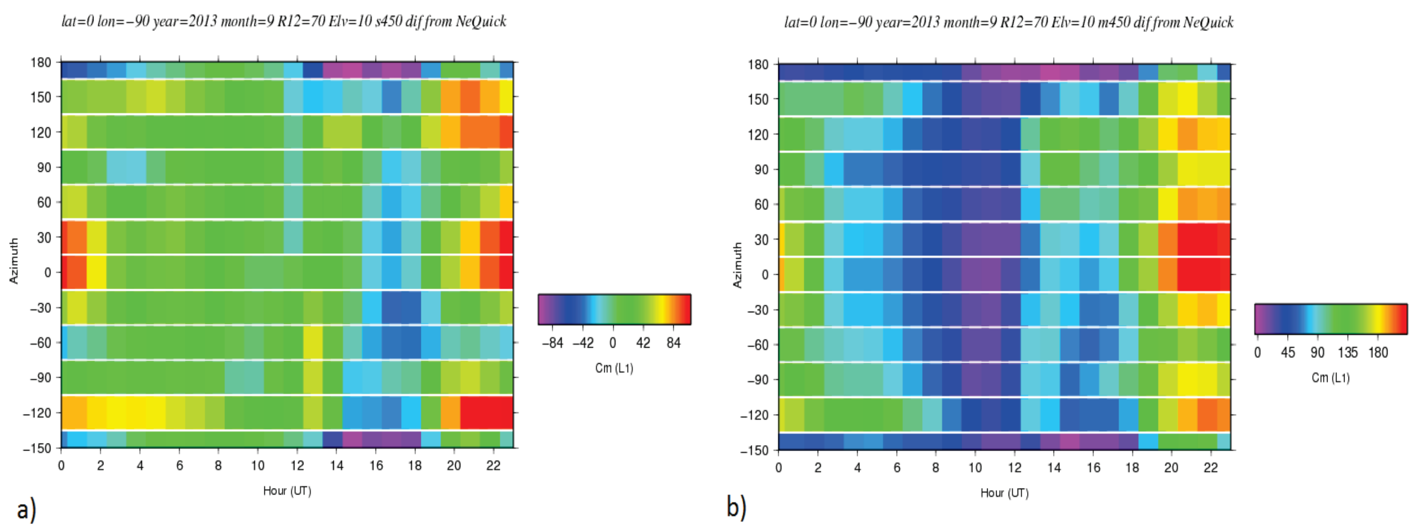

Figure 1- Slant delay difference on L1 caused by mapping function at 10 degree elevation angle at Lat= 0, Lon= -90, Year= 2013, Month= 9, R12= 70: a) NeQuick – Standard and b) NeQuick – Modified. Note different color scales.

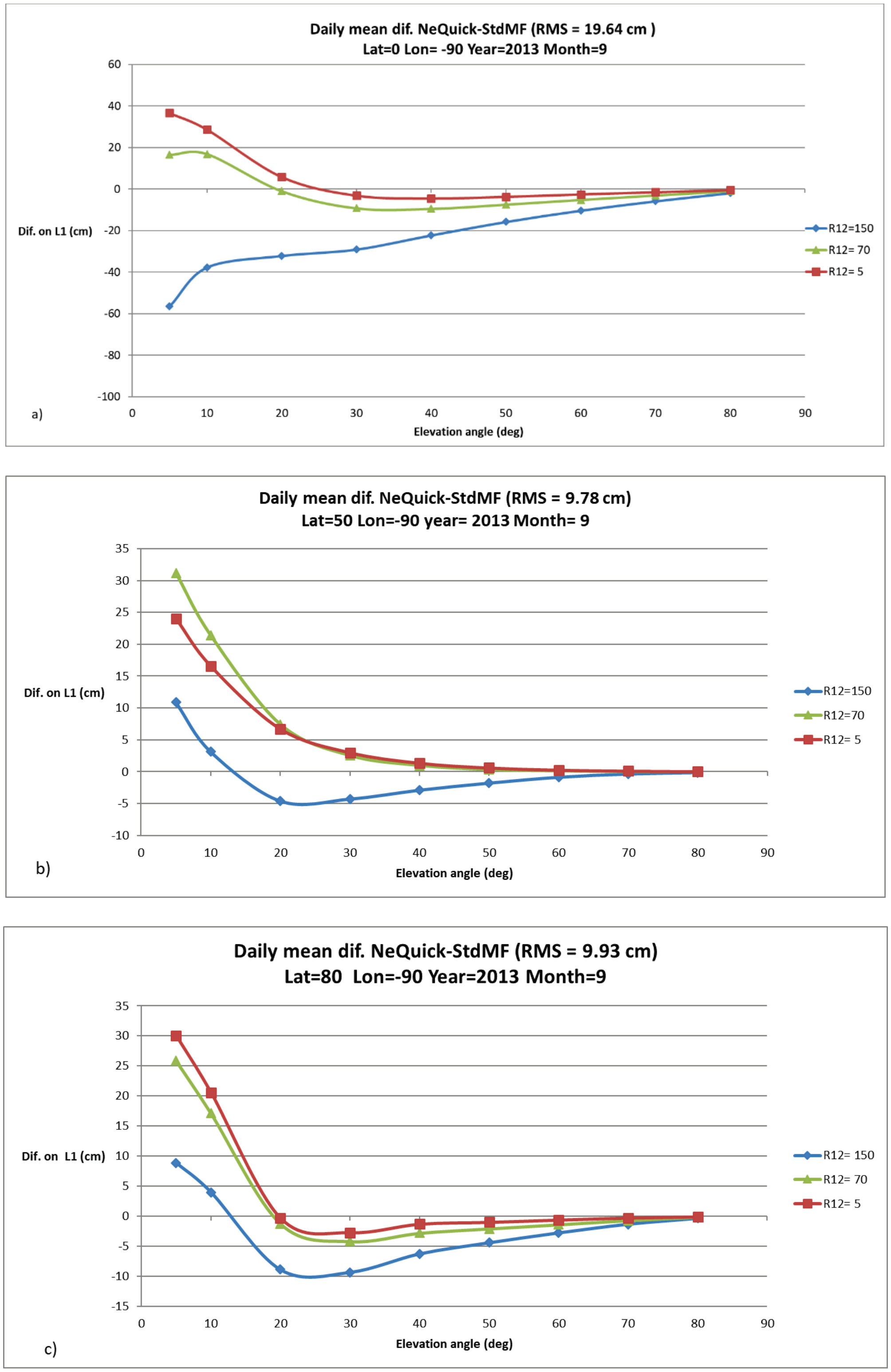

Figure 2- Daily mean slant delay difference on L1 caused by mapping function (NeQuick – Standard) at Lon= -90, Year= 2013, Month= 9: a) Lat=0 b) Lat= 50 c) Lat=80. [Note different vertical scales]

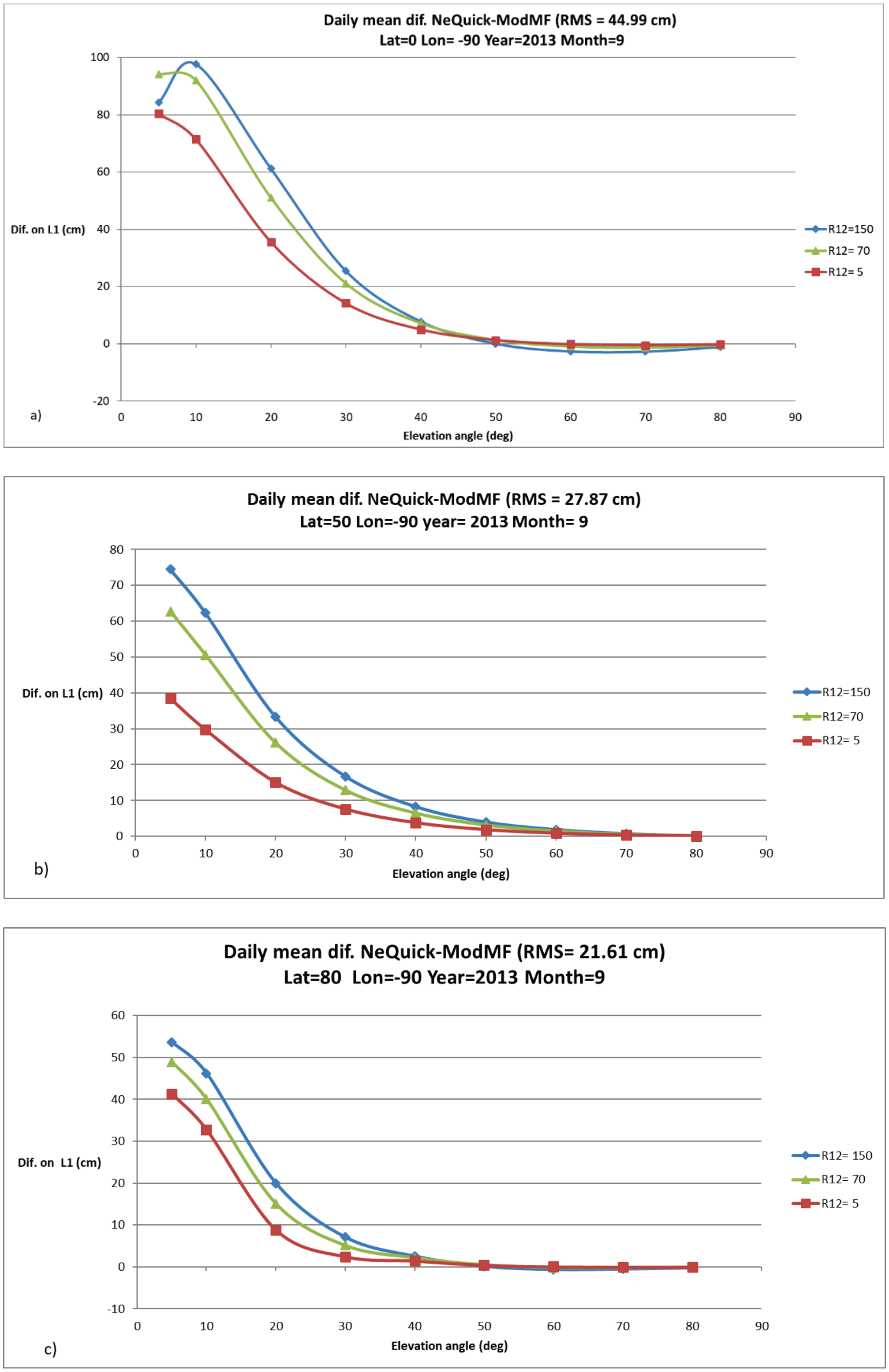

Figure 3- Daily mean slant delay difference on L1 caused by mapping function (NeQuick –Modified) at Lon= -90, Year= 2013, Month= 9: a) Lat= 0 b) Lat= 50 c) Lat= 80. [Note different vertical scales]

Comparing Standard and Modified mapping functions with the NeQuick based values during the studied scenarios show that Standard mapping function produced results closer to NeQuick (see figures 2 and 3 and overall RMS of the differences shown in each latitude). As expected, differences are larger over equatorial latitude where the RMS of differences for the standard mapping function over all elevation angles and R12 values reached to 19.64 cm whereas it reached to 44.99 cm for the modified mapping function. One may note from Figure 3 that the Modified mapping function resulted in smaller daily mean slant delays than those from NeQuick at elevation angles below 40 degrees in all studied scenarios. However, NeQuick is a semi-empirical model and is associated with errors depending on time and location. Looking at all ionization levels and locations chosen in this study shows that mapping functions provide very close results to those from NeQuick at elevation angles of 50 degrees and above.

VTEC values derived from NeQuick and used in equation (2) are plotted in Figure 4. In order to evaluate these values, VTEC at the same locations extracted from IGS final TEC maps over all days of September 2013 and are plotted in Figure 5. Comparing figures 4 and 5 shows that the three chosen levels of ionization used for the simulation studies above are fairly representative of VTEC at the studied locations and time. However, ionization level can be optimized to get closer NeQuick results to IGS values.

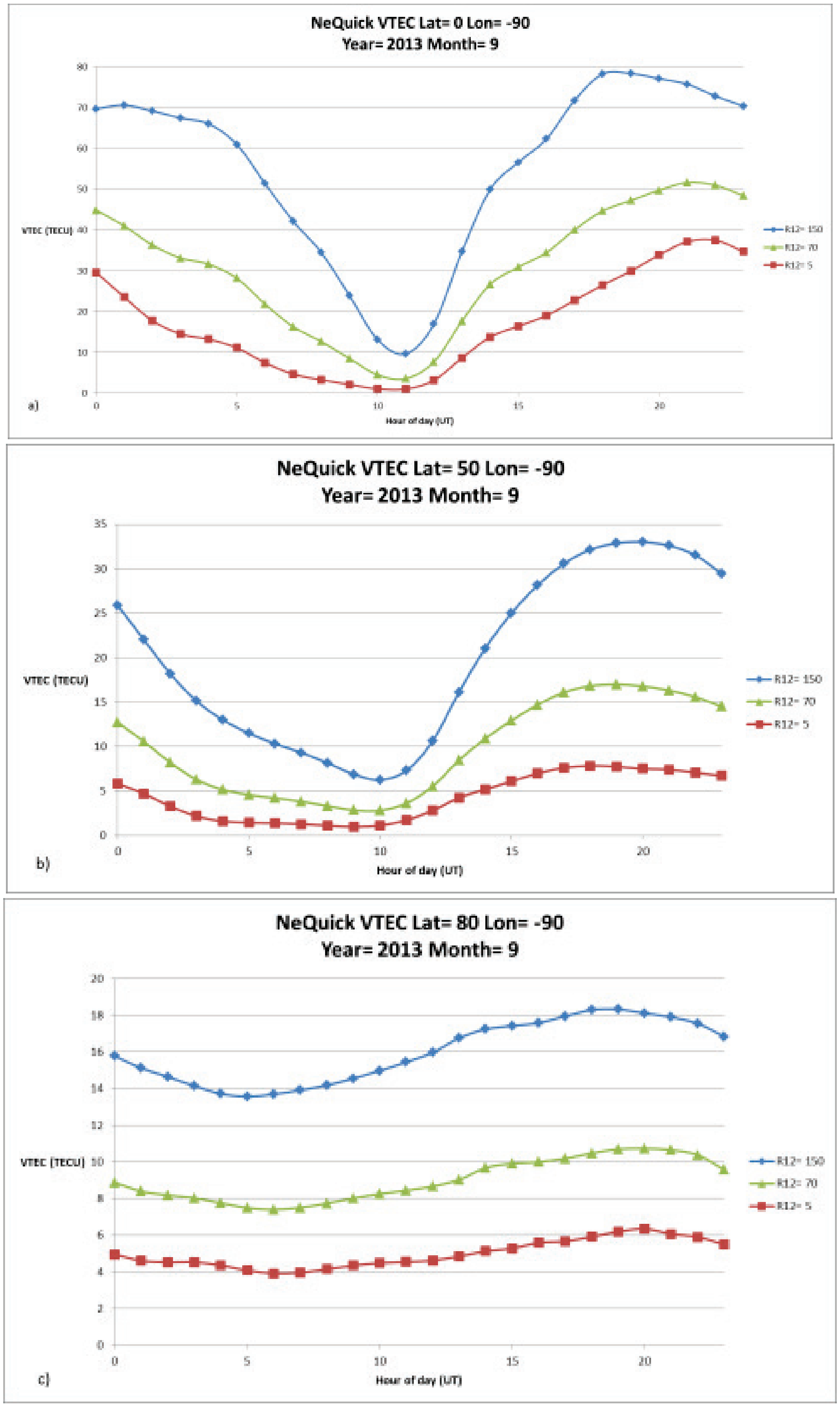

Figure 4 – NeQuick VTEC for Year= 2013, Month= 9, Lon= -90: a) Lat= 0 b) Lat= 50 c) Lat= 80. [Note different vertical scales]

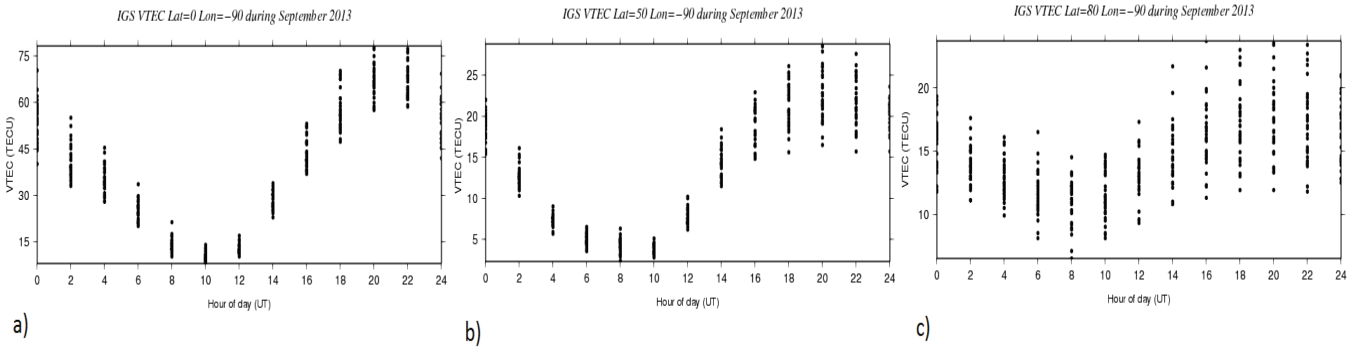

Figure 5 – IGS VTEC during September 2013 at Lon= -90 a) Lat= 0 b) Lat= 50 c) Lat= 80. [Note different vertical scales]

NeQuick based mapping functions at all azimuths, locations and ionization levels studied in this paper are plotted in Figure 6. A 3rd degree polynomial is fitted to NeQuick derived mapping function values as follow:

$$m_{Fit} = p_1 \cdot \chi^3 + p_2 \cdot \chi^2 - p_3 \cdot \chi + p_4$$
$$p_1 = -2.9657\mathrm{e}^{-6}$$
$$p_2 = 0.00079972 \qquad (4)$$
$$p_3 = -0.073171$$
$$p_4 = 3.2701$$

where χ is the elevation angle at the station.

This mapping function hereafter is referred to as Fit. NeQuick based values; Fit, Standard and Modified mapping functions are also plotted in Figure 6.

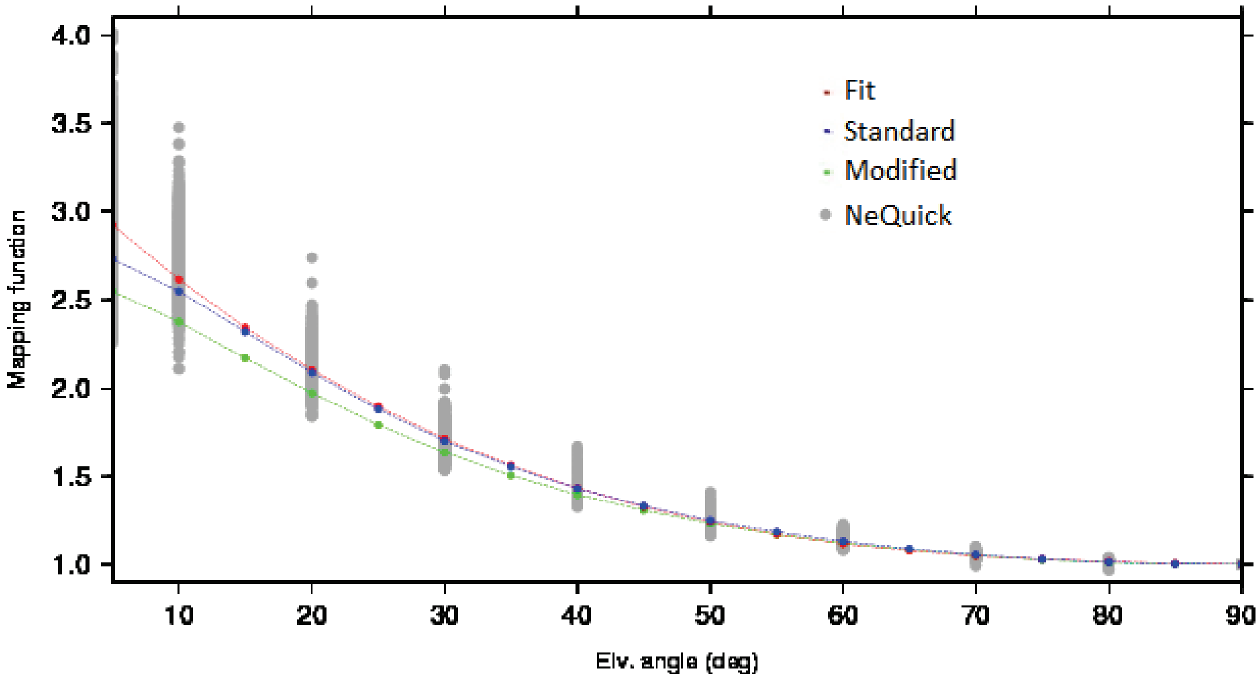

Figure 6 – Commonly used ionospheric mapping functions vs. NeQuick based mapping function at all studied locations and ionization levels studied in this paper.

Evaluation of mapping functions using coinciding IPPs

One may evaluate the performance of mapping functions by analysis of coinciding Ionospheric Pierce Points (IPPs) from all pairs of stations and satellites (See e.g. Komjathy et al., 2005 and Nava et al, 2007).

GPS stations used for routine daily VTEC map generation over most of North America [Ghoddousi-Fard et al., 2011] are employed for mapping function studies. VTEC is estimated based on a single layer model using geometry free phase observations levelled by code, corrected for station and satellite differential code biases (DCB). Coinciding IPPs are defined where two IPPs are closer than a certain distance following Nava et al. [2007]. VTEC difference from mixed receivers and satellites are affected by uncertainties in phase levelling, receiver and satellite DCB estimates, multipath and noise as well as mapping function uncertainties. Having an elevation cut-off angle of 10 degrees and ignorable (in nominal conditions) mapping function error at elevation angles of 50 degrees and above, VTEC difference from coinciding IPPs piercing the shell height at elevation angle differences of larger than 40 degrees may mostly include contribution of mapping function errors. Hence, a statistical analysis is performed at all possible coinciding IPPs with elevation angle difference of larger than 40 degrees processed using three different mapping functions namely: Fit, Standard and Modified. Table 1 includes mean and standard deviation of absolute VTEC differences at coinciding IPPs. As can be seen in Table 1, Fit followed by Standard mapping function provided smaller VTEC differences at coinciding IPPs. This may indicate that during the studied period and locations these mapping functions performed better than the Modified mapping function. Even though the NeQuick derived values were based on the month of September, the results are also consistent with an arbitrary chosen day in the following month of October.

Table 1- Mean and standard deviation of absolute difference between VTEC at coinciding IPPs from about 60 GPS stations over North America resulting from processing using three different mapping functions.

Date	Mean (TECU)			Standard deviation (TECU)			No. of coinciding IPPs
	Fit	Standard	Modified	Fit	Standard	Modified	
15 Sept, 2013	1.98	2.00	2.22	1.83	1.83	2.03	184*2
28 Sept, 2013	2.31	2.36	2.57	1.73	1.76	1.92	191*2
28 Oct, 2013	2.16	2.22	2.39	1.55	1.59	1.74	230*2

Conclusions

Two commonly used geometric mapping functions based on a single layer model were compared with slant to vertical TEC ratio from NeQuick. The comparison showed that at low elevation angles the difference caused by mapping function may reach up to a meter level during moderate ionospheric conditions. A fit to the NeQuick derived mapping function values resulted in an empirical mapping function which performed slightly better than commonly used mapping functions when VTEC at coinciding IPPs are compared. Further evaluations during different ionospheric conditions and tuning models based on real-time ionospheric conditions may result in improved mapping functions.

Acknowledgements

The Aeronomy and Radio Propagation Laboratory of the ICTP is thanked for making the NeQuick source code available.

References

Beutler, G., H. Bock, R. Dach, P. Fridez, A. Gäde, U. Hugentobler, A. Jäggi, M. Meindl, L. Mervart, L. Prange, S. Schaer, T. Springer, C. Urschl, and P. Walser (2007). Bernese GPS Software Version 5.0. Astronomical Institute, University of Bern, Bern, Switzerland.

Coster A. J., Gaposchkin, E. M., Thonton, L. E. (1992). Real-Time Ionospheric Monitoring System Using the GPS. Technical Report 954, Lincoln Laboratory, Massachusetts Institute of Technology, MA, USA.

Ghoddousi-Fard, R., P. Héroux, D. Danskin, and D. Boteler (2011). Developing a GPS TEC mapping service over Canada. Space Weather, Vol. 9, S06D11, doi: 10.1029/2010SW00062.

Ghoddousi-Fard R. and F. Lahaye (2016). Evaluation of single frequency GPS precise point positioning assisted with external ionosphere sources. vol. 57, pp. 2154-2166, Adv. Space Res. doi: 10.1016/j.asr.2016.02.017.

Hochegger G. B. Nava, S. M. Radicella, R. Leitinger (2000). A family of ionospheric models for different uses. Physics and Chemistry of the Earth, Part C: Solar, Terrestrial & Planetary Science 25(4), 307–310.

Komjathy, A., A. J. Mannucci, L. Sparks, A. Coster (2005). The ionospheric impact of the October 2003 storm event on WAAS. GPS Solutions 9, 41–50.

Memarzadeh Y. (2009). Ionospheric Modelling for Precise GNSS Applications. Publication on Geodesy 71, Netherlands Geodetic Commission, Delft, the Netherlands.

Nava B., S. M. Radicella, R. Leitinger, and P. Coïsson (2007). Use of total electron content data to analyze ionosphere electron density gradients. Advances in Space Research 39, 1292-1297.

Nava B., P. Coïsson, and S. M. Radicella (2008). A new version of the NeQuick ionosphere electron density model. Journal of Atmospheric and Solar-Terrestrial Physics 70, 1856-1862, doi: 10.1016/j.jastp.2008.01.015.

Schaer, S. (1999). Mapping and Predicting the Earth's Ionosphere Using the Global Positioning System. Ph.D. dissertation, University of Bern, Bern, Switzerland, 205 pp.

Schüler, T., and O. A. Oladipo (2013). Single-frequency single-site VTEC retrieval using the NeQuick2 ray tracer for obliquity factor determination. GPS Solutions, doi: 10.1007/s10291-013-0315-y.