Evaluation of the NeQuick model in Southern mid-latitudes using South African co-located GPS and Ionosonde data

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Abstract. This work investigates the performance of the NeQuick model in southern mid-latitudes. The NeQuick is used among others for the European Geostationary Navigation Overlay Service (EGNOS), developed to supplement the GNSSs systems by reporting on the reliability and accuracy of the positioning data. It is used by recommendation the International Telecommunication Union-Radiocommunication Sector (ITU-R), to compute the estimated total electron content (TEC) along the ray path of the signal from satellite to the GNSS receiver. The performance of the NeQuick is evaluated after it is adapted to the local conditions by ingesting the foF2 and M(3000)F2 recorded by the means of the Ionosonde at Hermanus (34.40°S; 19.20°E, South Africa). It is then used to compute a theoretical TEC above Hermanus and compared to the observed TEC derived from the co-located GPS receiver which belongs to the TrigNet network. To evaluate the model under different geomagnetic activity states we select three days each of quiet and magnetically disturbed days according to different solar activity indicators. It has been noticed that the ionosonde parameters allowed the model to get rid of the geomagnetic condition obstacle with RMSs almost similar for quiet and disturbed days. The NeQuick is significantly better for periods of minimum and moderate solar activity while it shows a large discrepancy during epochs of high solar activity.

1. Introduction

The accuracy of the position and time information provided by the Global Navigation Satellite Systems (GNSSs) is affected by several factors such as the troposphere, multipath and the ionosphere which is the most significant factor (See table 1). The satellite signal undergoes a time delay due to free electrons of the ionosphere. The effect of the delay on the pseudo-range computing can be minimized by using dual frequency signals (L1 and L2). For Single Frequency (SF) receivers, which still represent 75% of the market, the errors in positioning can reach 100 m under conditions of severe ionospheric disturbances. Single Frequency receivers rely on models such as the Klobuchar model, which is incorporated in the receivers, to compute the ionosphere total electron content (TEC) and then allows one to reduce the effect of the ionospheric delay. For Galileo SF receivers the NeQuick model

has been chosen for the ionospheric effect correction [1]. Several studies have been done to evaluate and improve the NeQuick model [1][2][3]. For these studies the following variables which affect the characteristics of the ionosphere have been considered: solar activity, geomagnetic activity, latitude, and time of day. This paper presents the assessment of the accuracy of the NeQuick model for the Southern mid-latitudes. It follows the method used in the study carried out by [4] who used co-located GPS and Ionosonde data in Europe (Northern mid-latitudes). We have adapted the NeQuick to the local conditions by ingesting "ionosonde parameters" recorded at Hermanus (34.4^{0}S; 19.2^{0}E, South Africa). The modified NeQuick is then used to compute a theoretical TEC above Hermanus and this TEC value is compared with the observed TEC derived from the co-located GPS receiver. The study reported here extends the work of [4] by also considering magnetically quiet and disturbed days in order to improve the ionospheric correction related to geomagnetic activity level. We selected three days corresponding to Minimum, Moderate and Maximum solar activity for each geomagnetic activity level.

Table 1. Typical contributions to the position error from various elements in GNSS systems [5].

Factor of error	Typical error
Ephemeris	2.1 m
Satellite Clock	2.1 m
Ionosphere	4.0 m
Troposphere	0.7 m
Multipath	1.4 m
Receiver	0.5 m

2. NeQuick

NeQuick is known as a quick-run model in computing the electron density and the TEC by numerical integration. It is considered suitable for trans-ionospheric applications [1]. This model has been developed at the Aeronomy and Radiopropagation Laboratory of the Abdus Salam International Centre for Theoretical Physics (ICTP) - Trieste, Italy and at the Institute for Geophysics, Astrophysics and Meteorology (IGAM) of the University of Graz, Austria. The NeQuick model calculates the ionospheric electron density profile by relying on three anchor points: E, F1 (if present) and F2 which represents the peaks of the different ionosphere layers. The anchor points are defined by providing the ionosonde parameters foE, foF1, foF2 and M(3000)F2. These parameters are computed by default by built in models but can also be provided to the model by ingesting observed data (See figure 1). The NeQuick model runs in Fortran code and computes the electron density by one to three "Epstein layers". The shape of an Epstein layer is given by the following function [4]:

$$N_L(h) = 4\mathrm{N}_{\max}\frac{\exp\left(\frac{\mathrm{h}-\mathrm{h}_{\max}}{\mathrm{B}_{\mathrm{L}}}\right)}{\left[1+\exp\left(\frac{\mathrm{h}-\mathrm{h}_{\max}}{\mathrm{B}_{\mathrm{L}}}\right)\right]^2} \tag{1}$$

where, B_L is the thickness parameter of the layer L.

The inputs to the NeQuick model are the geographic position, the time and the solar index (F10.7 or R12). The latest version of the model is NeQuick 2. For this study the NeQuick 1 version was used

since this version is being assessed by the European Space Agency (ESA). More details about the NeQuick model can be found in the work of [1]. NeQuick was implemented in the Global Ionospheric Scintillation Model (GISM) to calculate the background ionosphere. In Australia, it has been used in a simulation toolkit for a future GNSS in development. IRI -2007 uses NeQuick for the description of topside parameters. The most important use of the NeQuick model is its adoption by ESA for ionospheric delay correction in Galileo Single Frequency receivers The NeQuick in Galileo SF (future European GNSS) will be driven by an ”effective ionization level” Az defined as follows:

$$Az(\mu) = a_0 + a_1\mu + a_2\mu \tag{2}$$

where μ is the modified dip latitude (MODIP) [5]. The coefficients a_0, a_1 and a_2 are broadcast by EGNOS to the GNSS receivers and allows Az calculation at any wanted location. For the European Geostationary Navigation Overlay Service (EGNOS) developed to supplement the GNSSs systems, those coefficients are broadcast in band L1 (1575.42 MHz), and then Az is used as input by NeQuick instead of the solar flux F10.7 to compute the TEC. The ionosphere time delay in L1 can be determined as follows:

$$dt = \left(\frac{K \bullet TEC}{f^2}\right) \tag{3}$$

Where dt is the time delay in s, f the signal frequency in MHz, $K=1.34.10^{-3}$ $m^2s^{-1}TECu^{-1}$ and TEC is the Total Electron Content along the ray path expressed in TEC units (TECu) (1 $TECu=1x10^{16}$ electrons/m^2) .

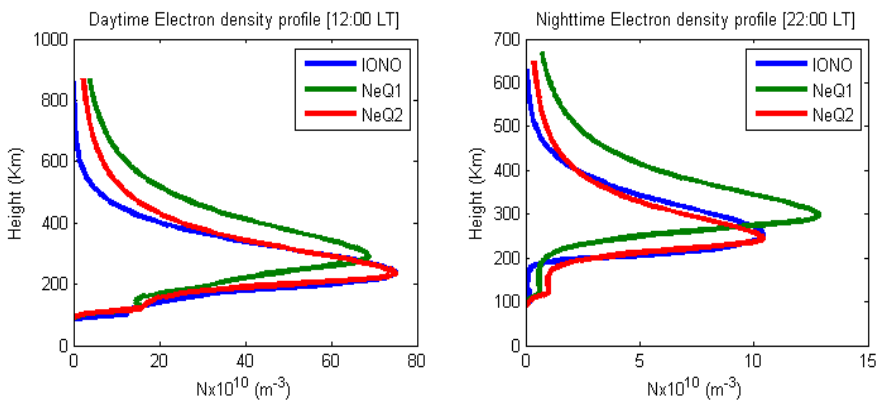

Figure 1: Evaluation of the NeQuick1 before (NeQ1) and after (NeQ2) ingestion of foF2 and M(3000)F2 recorded at the Hermanus Ionosonde station (IONO) for daytime and nighttime cases. NeQ2 presents a better match with the ionosonde observations (IONO).

3. Data and Processing

TEC NeQuick1 was used to obtain vertical TEC (NeQ TEC) above Hermanus after ingesting the foF2 and M(3000)F2 recorded by the means of Ionosonde at Hermanus (34.40°S; 19.20°E). The Hermanus Ionosonde, the fourth of the South African Network has been in operation since July 2008 so our study is limited from this year. This station consists of one transmitter and four receiver antennas and a DPS-4D Digisonde from the University of Massachusetts Lowell Center for Atmospheric Research (UMLCAR). The NeQ-TEC computed for each hour of the selected days has then been compared to the observed TEC (GPS TEC) derived from co-located GPS receiver which belongs to the TrigNet

network (http://www.trignet.co.za). The GPS data are stored in Receiver Independent Exchange format (RINEX) and the TEC values are determined by using the Gopi v2.2 software free available on internet. In our limited years of study (from 2008 to 2013), the monthly solar flux F10.7 varies from 68 to 153 solar flux units (s.f.u.), thus the months have been classified in different solar epochs according to this range. Using the Dst (Disturbance Storm-Time) index available on the internet (http://wdc.kugi.kyoto-u.ac.jp), we have chosen for each selected month one quiet day (Dst≈0nT) and one disturbed day (Dst <-50nT).

4. Results and Discussion

The results of this investigation are shown in figure 2 in which each row consists of two days of the selected month according to the solar activity. Figure 2 reveals that in general the magnetic activity level does not affect on the accuracy of NeQuick. For instance, the modelled TEC is closer to the observed TEC on day 4 (disturbed day) than on day 3 (quiet day). The discrepancies between the model and the GPS data are highest in the month of highest solar activity. NeQ TEC does not present a peak contrary to the other epochs where the peak appears near mid day. In the same month, the influence of the magnetic activity level is brought to light by a totally different behaviour of the two models for TEC as shown on day 6. The largest difference occurs during the main phase of the geomagnetic storm and tends to disappear with the recovery phase 18:00 UT (20:00 LT) to midnight. The contribution of this study is clearly demonstrated by Figure 3 which shows the difference between the GPS TEC and NeQ TEC (TECdiff). For the months of minimum and moderate solar flux, ΔTEC (GPS TEC-NeQuick TEC) remains below 6 TECu while it reaches 14 TECu during the epoch of

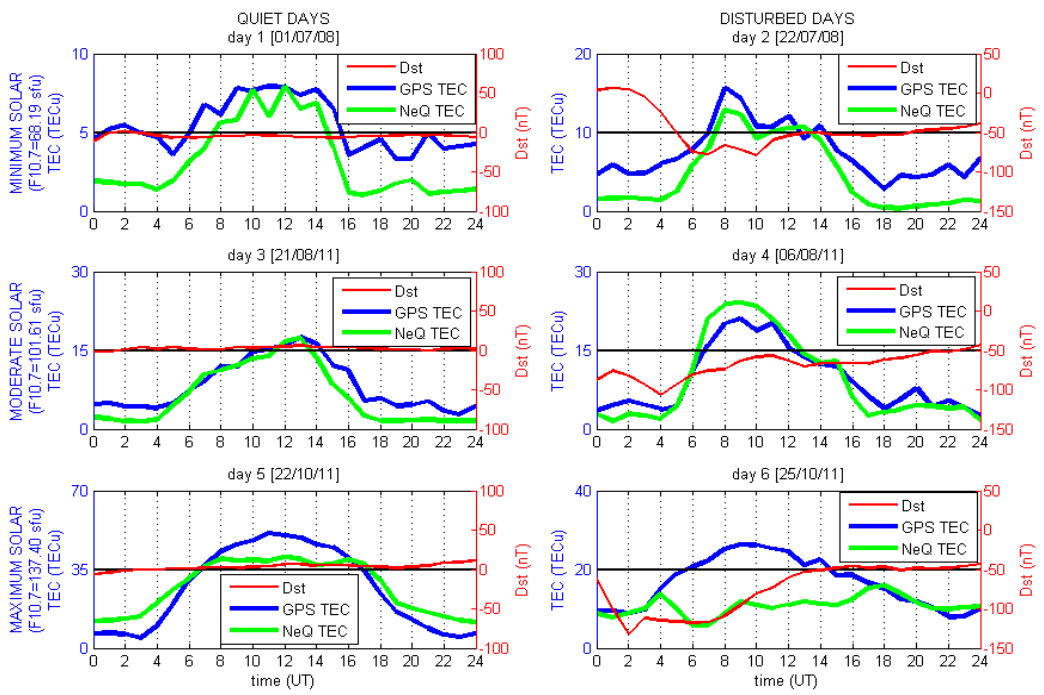

Figure 2: Comparison between the NeQuick TEC (NeQ TEC) and the GPS TEC above Hermanus for three different solar activity levels. The different solar activity levels are expressed by the F10.7 value (top: 68.19 sfu; middle: 101.61 sfu; bottom: 137.40 sfu) and by the geomagnetic activity by Dst (left=Dst≈0, right=Dst < −50 nT). The selected days are mentioned on top of every box

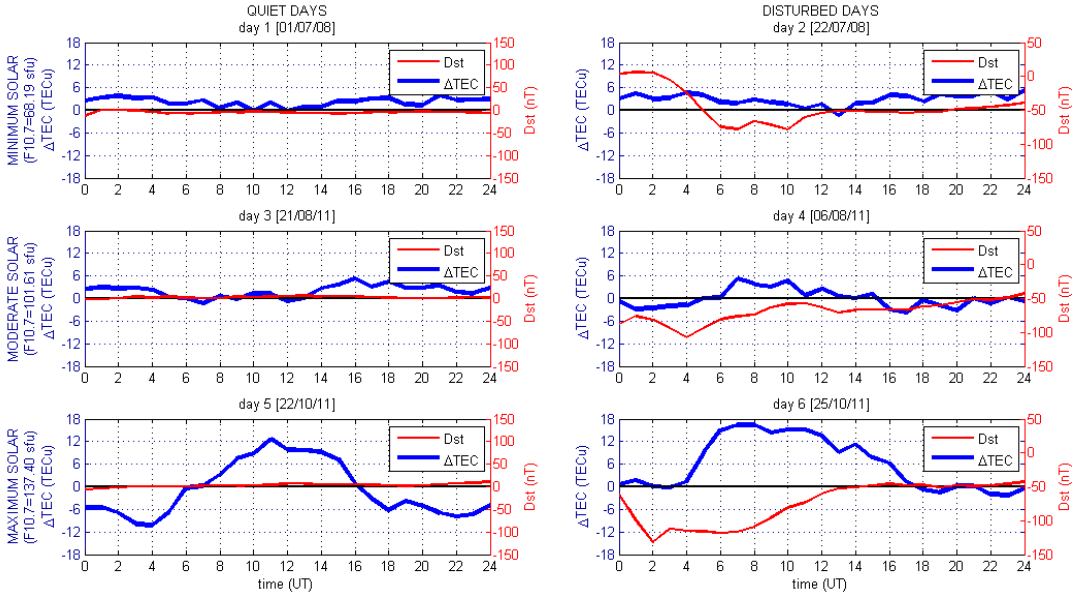

Figure 3: The difference between the GPS TEC and NeQuick TEC. The parameters of the panels are the same as in Figure 2.

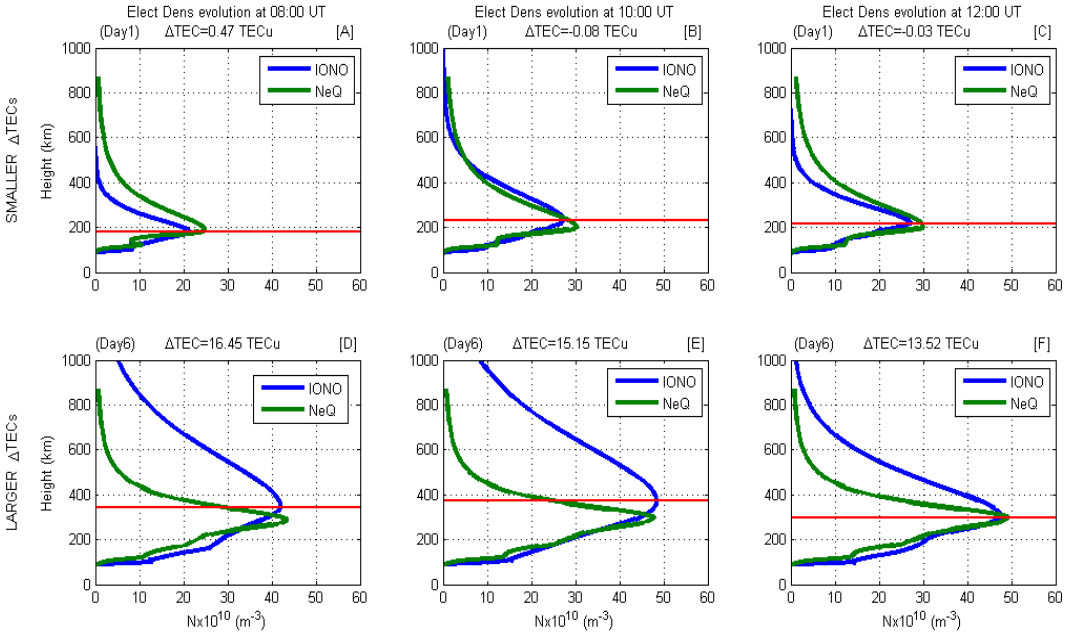

Figure 4: Comparison between the electron density profiles from the NeQuick model (NeQ) and from ionosonde data (IONO). The top and bottom set of 3 panels are for different times of respectively day 1 and day 6 of Figure 2. ΔTEC is given at the top of each panel. The F2 peak height hmF2 is indicated by the red line

maximum solar activity. Day 4, which is a geomagnetically disturbed day, nevertheless presents the smallest RMS difference (2.40 TECu) versus 2.45 and 2.52 TECu respectively for day 1 and 3, two

quiet days. Since the TEC is proportional to the peak electron density, we have also analysed the electron density profile provided by NeQuick. Seeing that GPS data does not provide the electron density directly (electron density can be obtained by a method of inversion) the electron density provided by the ionosonde was used for comparison with the NeQuick TEC (See Figure 4). Several studies like [6] have shown the strong correlation between GPS TEC and Ionosonde TEC. As seen in figure 3, the absolute value of ΔTEC is remains above 12 TECu from 06:00 to 12:00 UT on day 6 and below 2 TECu on day 1 at the same time-interval. Thus, three selected hours of this interval (08:00 UT, 10:00 UT and 12:00 UT) of those days have been used for this study. The results are shown in figure 4. These plots reveal that the lager ΔTECs are recorded when the F2 layer peak (hmF2) is higher than 300 km and the smaller ΔTECs are recorded when hmF2 is below 210 km. So, though F2 peak position in term of height (hmF2) and density (NmF2) is the "same" for the NeQuick and the ionosonde (figure 4F), ΔTEC (13.52 TECu) is large than the one shows on figure 4B (ΔTEC=0.08 TECu)

5. Conclusions

In this paper, we presented the assessment of the accuracy of NeQuick 1 or ITU-R over Hermanus, South Africa (34.40°S; 19.20°E). It has been found that NeQuick exhibits a weakness during a period where the solar flux is high with the difference between NeQuick TEC and Ionosonde TEC reaching 14 TECu. The lack of influence of the geomagnetic activity during the months of minimum and moderate solar activity has also been observed. The divergence between the model and the observation is a function of the F2 peak height hmF2, so during the hours and the days where the hmF2 is above 300 km, the model accuracy is worse. This study is a prelude to a further study on the evaluation of the models used by the GNSSs Single frequency (L1-only) receivers to reduce the ionospheric effect on GNSS position accuracy for the Southern mid-latitudes. It may provide useful information to advise users in this region on the choice of their GNSS equipment.

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