NeQuick G model performance for single-frequency users



Leistung des NeQuick G-Modells für Single-Frequency-Benutzer

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Abstract

The 3.5 years (2019/01-2022/06) evaluation of the NeQuick G model performance provided valuable insight into its accuracy and capability to model the ionosphere for single-frequency (SF) users during different ionospheric activity levels. In this study, the Vertical Total Electron Content (VTEC) accuracy, along with the horizontal and vertical position errors introduced by model deficiencies are investigated. In terms of Total Electron Content (TEC) accuracy and SF position accuracy, the NeQuick G model outperforms the Klobuchar model; therefore, the NeQuick G model might be more effective for mitigating the effects of ionospheric disturbances on SF Global Navigation Satellite Systems (GNSS) signals. In consequence, the TEC accuracy offered by the NeQuick G model can result in a more accurate positioning.

Keywords: Ionosphere, NeQuick G, Klobuchar

Kurzfassung

Die 3,5-jährige Evaluierung (2019/01-2022/06) der Qualität des NeQuick G-Modells lieferte wertvolle Einblicke in seine Genauigkeit und Fähigkeit, die Ionosphäre für Single-Frequency-Benutzer (SF) während verschiedener ionosphärischer Aktivitätsniveaus zu modellieren. In dieser Studie wird die Genauigkeit des modellierten vertikalen Total Electron Content (VTEC) sowie die durch Modellfehler verursachten horizontalen und vertikalen Positionsfehler untersucht. In Bezug auf die Genauigkeit des Total Electron Contents (TEC) und die SF-Positionsgenauigkeit übertrifft das NeQuick G-Modell das Klobuchar-Modell; daher könnte das NeQuick G-Modell wirksamer sein, um die Auswirkungen ionosphärischer Störungen auf die Signale des SF Global Navigation Satellite Systems (GNSS) abzuschwächen. Infolgedessen kann die TEC-Genauigkeit des NeQuick G-Modells zu einer genaueren Positionierung führen.

Schlüsselwörter: Ionosphäre, NeQuick G, Klobuchar

1. Introduction

The ionosphere is a part of the Earth's atmosphere, located between 50 km and 1000 km above the Earth's surface. The maximum electron density prevails in the layer between 250 km and 400 km. Due to its dispersive nature for microwaves, the ionosphere alters the propagation of radio signals, leading to measurement errors. This effect can be successfully mitigated by utilizing multi-frequency receivers, while single-frequency receivers must rely on a correction model. Hence, the performance of ionospheric models employed by existing Global Navigation Satellite Systems (GNSS) is a crucial factor in positioning. Neglecting changes in the ionosphere Total Electron Content (TEC) can introduce tens of meters of error in the position calculations.

The extensive recording of solar sunspot activity began in 1755. Currently, Solar Cycle 25 is active, which started in December 2019 with a minimum sunspot number of 1.8. It is expected to continue until about 2030. The NOAA/NASA co-chaired, international panel to forecast Solar Cycle 25, predicted in December 2019 that Cycle 25 will be average in intensity and similar to Cycle 24, with a peak in July 2025 (+/- 8 months), with a smoothed sunspot number (SSN) of 115 (NOAA, 2019). Additionally, the panel concurred that a solar minimum would occur in April 2020 (+/- 6 months). However, the observations from 2020 to 2022 (the first three years of the cycle) proved that Solar Cycle 25 intensified more rapidly than initially forecasted, significantly exceeding predicted values and having the potential for an exceptionally strong solar maximum. As a result, we can expect more frequent disturbances for GNSS positioning on particular days and locations.

This work investigates the patterns of TEC fluctuations over distinct zones, with a main focus on the European region, from 2019/01 to 2022/06.

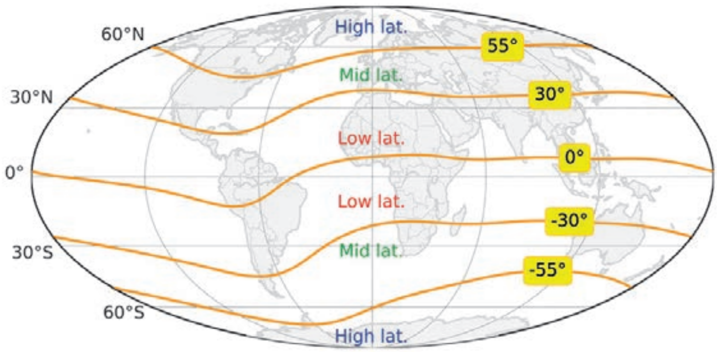

Fig. 1: Magnetic latitudes. Ionospheric activity is most intense at low latitudes (up to 100 days per year). At poleward latitudes, it is less frequent and it is least frequent at mid-latitudes, a few to ten days per year

Moreover, the Position, Velocity, and Time (PVT) accuracy is estimated. The study was performed as a response to an European Union Agency for the Space Programme / European GNSS Agency (EUSPA/GSA) call in the frame of the Galileo Reference Centre – Member States (GRC-MS) consortium, work package 3.4: NeQuick G model performance, as a collaborative work between TU Wien, Austria (TUW; mid-latitudes), and the Norwegian Mapping Authority, Norway (NMA; high- and low-latitudes).

1.1 Ionospheric activity

The ionosphere is constantly changing. The main components related to the variable ionospheric activity levels are the periodical solar activity cycles, Earth's orbit inclination (annual impact; increased ionospheric activity is observed at the spring and autumn equinoxes), Earth's rotation (daily impact; maximum ionospheric effects after local sunset until midnight), and interaction with the Earth's magnetic field. Additionally, the ionospheric activity is correlated with

1) Increased sunspot activity, which is linked to the 11-year solar cycle;
2) Solar storms, flares, and coronal mass ejections (CME); and
3) Location - the highest ionospheric activity is seen +/- 20 degrees around the geomagnetic equator and, less severely, in auroral (polar) regions (Figure 1).

To measure solar particle radiation by its magnetic effects, Julius Bartles introduced in 1949 the geomagnetic three-hourly Kp index (see Bartels, 1957). Today Kp is an important measure for the energy input from the solar wind to Earth, and it is used by weather services in near-real time. Kp goes back to 1932 and is an important parameter to investigate long-term climate change in the upper atmosphere, in the geospace, and in the solar wind. The Kp parameter is based on the data from 13 geomagnetic observatories around the globe. As observed by GFZ German Research Centre for Geosciences, in the 3.5 years study period, there were six geomagnetic storms (Kp-index > 6, Figure 2):

- May 14, 2019 (Kp-index 6.3)
- May 12, 2021 (Kp-index 7.0)
- October 12, 2021 (Kp-index 6.3)
- November 3-4, 2021 (Kp-index 7.7)
- March 13, 2022 (Kp-index 6.3)
- April 10, 2022 (Kp-index 6.7)

Interestingly, years with the most intense geomagnetic storms are not necessarily observed in a solar maximum.

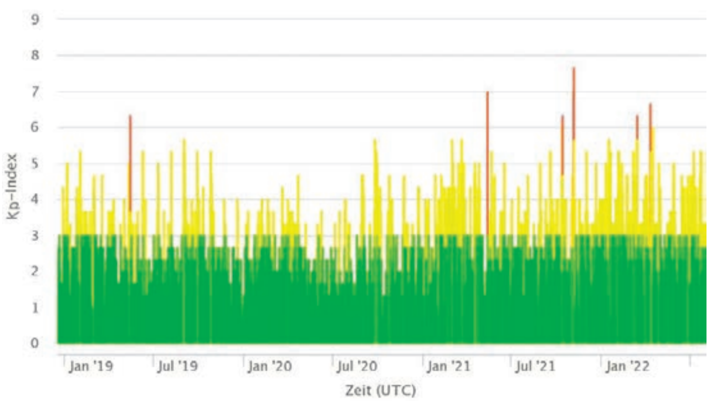

Fig. 2: Kp-index values in years between 1 January 2019 and 30 June 2022, as provided by GFZ German Research Centre for Geosciences (CC BY 4.0)

1.2 Ionospheric models

The propagation of radio waves is affected by the ionosphere, changing the signal path and velocity. Therefore, satellite navigation systems use ionospheric models to calculate and remove part of the ranging error caused by the ionosphere when single-frequency receivers are used. The Klobuchar model is an empirical model developed for single-frequency users. Approximately 50 % of the range error caused by ionospheric refraction can be corrected by applying the Klobuchar model. Its algorithm uses eight ionospheric coefficients, which can be found within the GPS navigation message (Klobuchar, 1987). The NeQuick G model is a three-dimensional and time-dependent ionospheric electron density model adapted to provide real-time Galileo single-frequency ionospheric corrections. These real-time predictions are based on solar-activity-related input values: sunspot number or solar flux, month, geographic latitude and longitude, height, and Universal Time (UT). NeQuick G is designed to achieve a correction capacity of at least 70 % of the ionospheric code delay across all locations, times of day, seasons, and levels of solar activity. However, it may be inefficient during significant ionospheric disruption (e.g., geomagnetic storms) (European Commission, 2016).

2. Methodology

The NeQuick G and Klobuchar models are evaluated in post-processing mode, using the validation station networks located in three geomagnetic-latitude regions (Figure 3). The total number of electrons present along a path between a radio transmitter and receiver is expressed as the Total Electron Content (TEC). To investigate the accuracy of the modeling, we present results of the Vertical Total Electron Content (VTEC), which is the vertically integrated electron density at a given location at a particular time. For ground-to-satellite communication and satellite navigation, TEC is a good parameter to monitor possible space weather impacts.

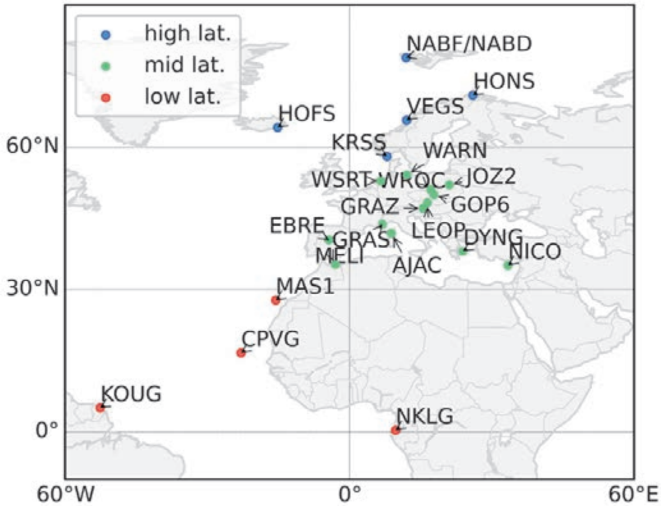

Fig. 3: Station validation map

2.1 VTEC accuracy

The VTEC accuracy, performed for the Galileo and the GPS constellations, is obtained following the three steps:

1) Computation of VTEC (every 5 min) using the navigation models (NeQuick G for Galileo and Klobuchar for GPS), for the set of satellites observed by the GNSS reference stations (Figure 3), using the actual observation geometry (receiver and satellite positions);
2) For the same set of points, the reference VTEC is computed. For NMA, the observed VTEC values are calculated every 5 min based on dual-frequency measurements from the GNSS reference stations (Figure 3). For the high-latitude stations, differential code biases (DCBs) are retrieved from the NMA's ionosphere monitoring system as the receivers used here are part of the much larger network processed by that system. For the low-latitude stations, DCBs are retrieved from the International GNSS Service (IGS) archives. For the mid-latitude stations, DCBs are obtained by a least squares adjustment based on P1 and P2 code observations, as well as satellite DCBs downloaded from the Astronomical Institute of the University of Bern (AIUB) CODE database. The standard Single Layer Model (SLM) is used to convert slant TEC to vertical TEC (ionosphere altitude 350 km);
3) The VTEC error is calculated as a difference between the model-derived VTEC values and the reference VTEC values obtained through the observations.

	High- and low latitudes (NMA)	Mid latitudes (TUW)
Software	Where (Kirkwik et al., 2017)	raPPPid[1] (Glaner, 2022)
Sampling rate	30 s	30 s
Elevation cutoff mask	5 deg	5 deg
Troposphere delay	GPT2w (Böhm et al., 2015)	VMF3 (Landskron and Böhm, 2018)
Solid Earth tides	applied	applied
Elev.-dep. weighting	1/sin(elev.)	1/sin^2(elev.)
Estimation	epoch-wise least square	Kalman filter
Estimated parameter	coordinates, receiver clock	coordinates, receiver clock, zenith wet delay
PDOP threshold	6	N/A

1) TUW open-source software: https://github.com/TUW-VieVS/raPPPid, https://vievswiki.geo.tuwien.ac.at/raPPPid

Tab. 1: Settings applied in each latitude region to calculate SF position accuracy

2.2 SF position accuracy

The position accuracy achieved by processing single-frequency (SF) observations along with respective ionospheric delay models was evaluated according to the following three steps:

1) The Galileo E1 SF solutions are calculated in post-processing mode based on 30 s RINEX files, whereby the applied settings are shown in Table 1;

2) The reference site positions are based either on the official International Terrestrial Reference Frame 2014 (ITRF2014) SINEX file station position and velocity solution (epoch 1st January 2010), extrapolated to the selected epoch from the analyzed quarter of observation (TUW) or yearly calculated ITRF2014 coordinates, referred to an epoch on 1st January of each year (NMA);

3) Coordinates obtained from the two SF solutions (either for Klobuchar or NeQuick G) are directly compared epoch-wise in a local topocentric coordinate system (East, North, Up) to the reference values in ITRF2014. Then, the daily single-frequency positioning errors were calculated as a mean of the 95th percentile (HPE95 and VPE95) for the reference stations. Hereby, epochs exceeding the Position Dilution of Precision (PDOP) threshold are excluded.

3. Results

3.1 VTEC maps

As follows from the Kp index values (Figure 2), in the 3.5 years of the study period the latest geomagnetic storm was observed on April 10, 2022. Therefore, to evaluate the NeQuick G and Klobuchar model performance in disruptive conditions, the VTEC maps for April 2022 are presented in Figure 4. The VTEC maps of the mid-latitude region (Europe) are based on a comparison of the NeQuick G and Klobuchar model w.r.t. the CODG global ionospheric maps. The reference global VTEC model CODG (Schaer et al., 1996) is generated daily by the Centre for Orbit Determination in Europe (CODE), University of Bern, Switzerland.

The plots display the 95^{th} percentile of the absolute VTEC differences (mean value of all days in April 2022), distributed over 12 2-hourly subplots. The absolute VTEC differences are expressed in Total Electron Content Units (TECU; 1 TECU = 10^{16} electrons/m^2). In Earth's ionosphere, TEC values can range from a few to several hundred TECUs.

In the time of increased ionospheric activity, the performance of both NeQuick G and Klobuchar models is poor (VTEC differences over 10 TECU), depending on the time and location. For NeQuick G, the largest discrepancies start at 00 UTC in the South (below 45 deg latitude) and evolve to the entire region over time. The underperformance of

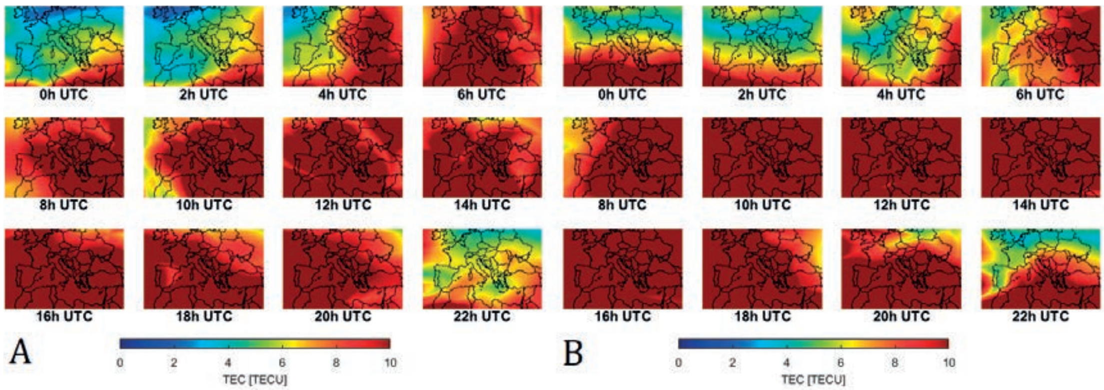

Fig. 4: *95th percentile of absolute VTEC differences for the NeQuick G (panel A) and Klobuchar (panel B) w.r.t. CODG model in April 2022*

the Klobuchar model is more pronounced, with large VTEC differences (over 10 TECU) between 10-16 UTC in the whole region. However, in times of moderate ionospheric activity (not shown), VTEC differences for the NeQuick G are most visible in the far South, reaching around 8 TECU at particular hours of the day only, whereas for the Klobuchar high VTEC differences cover the whole region for most of the day. The long-term evaluation of the VTEC trends in various ionospheric conditions is presented in Figure 5.

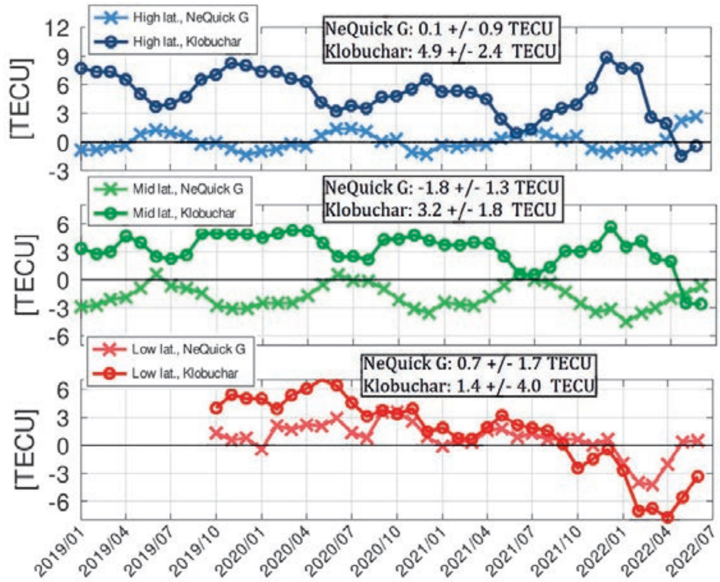

Fig. 5: *Monthly means of the VTEC error for the NeQuick G and Klobuchar model (NMA/TUW results). The top panel shows results for high latitudes, the middle panel for middle latitudes, and the bottom panel for low latitudes.*

3.2 VTEC error

Through the 3.5 years of investigations, the latitude zone-dependant monthly mean VTEC error for the NeQuick G and Klobuchar models was calculated (Figure 5). Besides, the average VTEC error values together with the standard deviations for both tested models are presented.

Overall, the NeQuick G model outperforms the Klobuchar model (smaller average VTEC error values and their standard deviations). Due to increasing ionization levels and space weather activity as the Solar Cycle 25 approaches its maximum, starting from 2022/04 (high/mid lat) and 2022/01 (low lat) larger VTEC discrepancies are observed.

3.3 Position error

As noted the ionosphere affects the propagation of electromagnetic waves, which can cause GNSS positioning problems or disturbances in connection with the GNSS satellites. To evaluate, if the applied ionospheric model has an impact on the estimated position for single-frequency users, the horizontal and vertical position errors were calculated (Figure 6).

The value of the horizontal position error depends mainly on the latitude region. For the high- and mid-latitudes, the horizontal position error (HPE95) is below 2 m, whereas for low latitudes the error

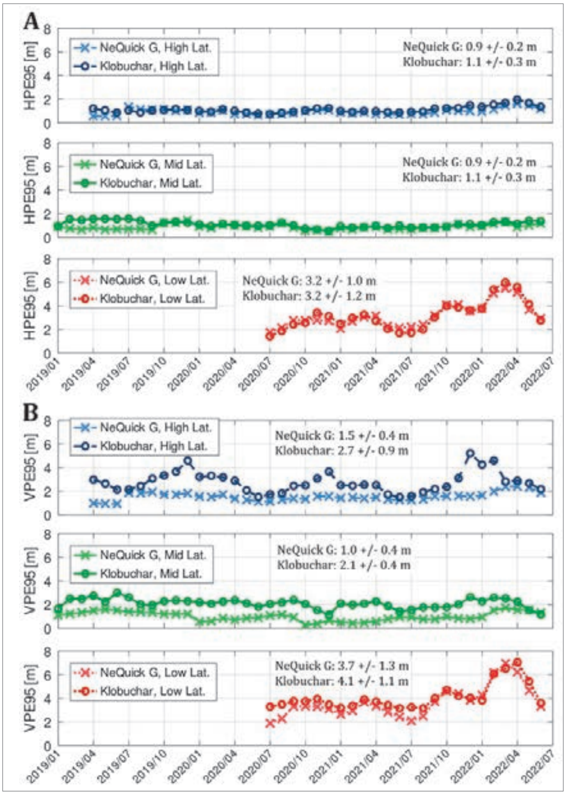

Fig. 6: Monthly mean horizontal position error (HPE95; panel A) and vertical position error (VPE95; panel B)

is up to 6 m, regardless of the applied ionospheric model. In terms of the vertical component, the NeQuick G model outperforms the Klobuchar. The largest VPE95 values (up to 8 m) are obtained for the low latitude region, reaching the maximum at the beginning of 2022.

4. Conclusions

Over a period of 3.5 years (2019/01-2020/06), the performance of the NeQuick G and Klobuchar model has been investigated. Although unstable ionospheric conditions are challenging for both, the NeQuick G and Klobuchar model, the NeQuick G provides a better performance in terms of VTEC representation (smaller average mean VTEC errors) as well as ionospheric delay correction of GNSS observations subsequently used in positioning with SF user sensors (smaller average mean HPE95/VPE95 errors) compared to Klobuchar. The lower latitudes are under the highest influence of ionospheric activity, which is reflected in both VTEC and position error results.

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References

[1] *Bartels, J. (1957)*: The geomagnetic measures for the time-variations of solar corpuscular radiation, described for use in correlation studies in other geophysical fields. Ann. Intern. Geophys., 4, 227-236.

[2] *Böhm, J., Möller, G., Schindelegger, M., Pain, G., & Weber, R. (2015)*: Development of an improved empirical model for slant delays in the troposphere (GPT2w). GPS solutions, 19, 433-441.

[3] *European Commission (2016)*: European GNSS (Galileo) Open Service – Ionospheric Correction Algorithm for Galileo Single Frequency Users.

[4] *Glaner, M. F. (2022)*: Towards instantaneous PPP convergence using multiple GNSS signals (Doctoral dissertation, Wien).

[5] *Kirkvik, A. S., Hjelle, G. A., Dahnn, M., Fausk, I., & Mysen, E. (2017, November)*: Where - a new software for geodetic analysis. In 23rd European VLBI Group for Geodesy and Astrometry Working Meeting (Vol. 23, pp. 248-252).

[6] *Klobuchar, J. A. (1987)*: Ionospheric time-delay algorithm for single-frequency GPS users. IEEE Transactions on aerospace and electronic systems, (3), 325-331.

[7] *Landskron, D., & Böhm, J. (2018). VMF3/GPT3*: refined discrete and empirical troposphere mapping functions. Journal of Geodesy, 92, 349-360.

[8] *NOAA. (2019)*: Solar cycle 25 forecast update. Solar Cycle 25 Forecast Update | NOAA / NWS Space Weather Prediction Center. https://www.swpc.noaa.gov/news/solar-cycle-25-forecast-update.

[9] *Schaer, S., Beutler, G., Mervart, L., Rothacher, M., & Wild, U. (1996)*: Global and regional ionosphere models using the GPS double difference phase observable. In Proceedings of the IGS Workshop.

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