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Locally adapted NeQuick 2 model performance in European middle latitude ionosphere under different solar, geomagnetic and seasonal conditions

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Abstract

The ionosphere introduces positioning error in Global Navigation Satellite Systems (GNSS). There are several approaches for minimizing the error, with various levels of accuracy and different extents of coverage area. To model the state of the ionosphere in a region containing low number of reference GNSS stations, a locally adapted NeQuick 2 model can be used. Data ingestion updates the model with local level of ionization, enabling it to follow the observed changes of ionization levels. The NeQuick 2 model was adapted to local reference Total Electron Content (TEC) data using single station approach and evaluated using calibrated TEC data derived from 41 testing GNSS stations distributed around the data ingestion point. Its performance was observed in European middle latitudes in different ionospheric conditions of the period between 2011 and 2015. The modelling accuracy was evaluated in four azimuthal quadrants, with coverage radii calculated for three error thresholds: 12, 6 and 3 TEC Units (TECU). Diurnal radii change was observed for groups of days within periods of low and high solar activity and different seasons of the year. The statistical analysis was conducted on those groups of days, revealing trends in each of the groups, similarities between days within groups and the 95th percentile radii as a practically applicable measure of model performance.

In almost all cases the modelling accuracy was better than 12 TECU, having the biggest radius from the data ingestion point. Modelling accuracy better than 6 TECU was achieved within reduced radius in all observed periods, while accuracy better than 3 TECU was reached only in summer. The calculated radii and interpolated error levels were presented on maps. That was especially useful in analyzing the model performance during the strongest geomagnetic storms of the observed period, with each of them having unique development and influence on model accuracy. Although some of the storms severely degraded the model accuracy, during most of the disturbed periods the model could be used, but with lower accuracy than in the quiet geomagnetic conditions. The comprehensive analysis of locally adapted NeQuick 2 model performance highlighted the challenges of using the single point data ingestion applied to a large region in middle latitudes and determined the achievable radii for different error thresholds in various ionospheric conditions.

Keywords: NeQuick 2; Local model adaptation; Ionospheric error; TEC; Middle latitudes; GNSS

1. Introduction

Modern technologies depend heavily on satellite positioning and benefit of its accuracy. Among several factors that affect performance of Global Navigation Satellite Systems (GNSS), such as satellite clock and ephemeris accuracy, receiver clock accuracy, receiver noise, multipath effects, tropospheric delay, biases and interference, the influence of ionospheric delay is one of the most important (Misra and Enge, 2013). Due to the refraction caused by the presence of charged particles in the ionosphere,

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electromagnetic signals experience group delay and phase advance while passing through. GNSS base the position calculation on measuring signal travel times between the satellites and a receiver, which are then translated into distances. Ionospheric signal delay introduces error in distance calculation, and consequently decreases positioning accuracy. The structure and the dynamics of the ionosphere are very complex, depending on the geomagnetic field structure, observed location (i.e. geomagnetic longitude), time of day, time of year, solar 11-year cycle and conditions on the Sun (Zolesi and Cander, 2014).

There are multiple approaches for reducing the effects of ionospheric delay. Due to the frequency dependency of the refractive index, by using two frequencies it is possible to eliminate ionosphere-caused error almost completely, removing the first order of the error (Hoque and Jakowski, 2006). However, vast majority of GNSS receivers are lower priced single frequency receivers. These receivers rely on ionospheric models, e.g. Klobuchar model in GPS (Klobuchar, 1987) and NeQuick G model in Galileo (European Commission, 2016), or on external information on ionosphere such as Satellite and Ground Based Augmentation Systems (SBAS and GBAS). Ionospheric models incorporated within the systems have the advantage of global coverage, but the accuracy is not ideal in all ionospheric conditions and in every particular location. Maximal residual error defined in GPS and Galileo documents ranges between 50% for Klobuchar model (USA DoD, 2008) and 30% for NeQuick G model (European Commission, 2016). Regional augmentation systems provide information on ionospheric conditions over the covered area with very good accuracy as they rely on real-time data from the region of interest. However, only parts of land masses of the northern hemisphere are covered by SBAS (Airports Authority of India, 2013; European GNSS Agency, 2015; Russian Space Systems, 2012; Tashiro, 2016; USA DoT and FAA, 2008). Oceans and other land masses in the northern hemisphere, as well as the whole southern hemisphere currently cannot benefit of this type of ionospheric error correction. Global Ionospheric Maps (GIMs) provide ionospheric data derived from numerous reference GNSS stations available around the world. Those maps have very high accuracy over the areas with dense station distribution, but over the oceans and remote land areas, values are interpolated and could differ significantly from the actual ionospheric conditions (Hernandez-Pajares et al., 2016).

To improve ionospheric correction for single-frequency receivers in a targeted area, for instance some of the areas not covered by SBAS or a sufficiently accurate GIM, global ionospheric models such as NeQuick 2 can be locally adapted (Nava et al., 2006). NeQuick 2 is the latest version of the NeQuick ionospheric model (Radicella and Nava, 2010) with improvements over the first version, especially in the topside calculation, resulting in better overall performance (Bidaine and Warnant, 2010). The model is suitable for local adaptation due to the input flexibility. It is also specific by the ability to profile the electron distribution in the ionosphere, avoiding the use of mapping function, which is required in Klobuchar and other models that rely on single layer approximation of the ionosphere. Modified geomagnetic dip latitude is used to adapt the model calculations across different locations, achieving the balance between geomagnetic coordinates used near the geomagnetic equator and geographic coordinates used closer to the poles. In the process of adaptation, the global model can be tuned to fit reference data of the targeted region, derived from ionosondes, Low Earth Orbit (LEO) satellites or reference GNSS stations. Accuracy of the adapted model generally decreases with distance from the model fitting location. The process of data ingestion is well described, but the extent of the area accurately covered by such model is strongly dependent on ionospheric conditions.

The goal of the research described in this paper was to evaluate the performance and determine the usable radius of NeQuick 2 model locally adapted by GNSS reference station derived TEC during different ionospheric conditions in middle latitudes, as there were no studies that systematically analyzed the geographical extent of locally adapted NeQuick 2 model coverage. In this research the characteristic periods with specific ionospheric conditions were selected from the current solar cycle. The model performance was analyzed statistically and the achievable radii were determined for different error thresholds and different geographic quadrants in selected ionospheric conditions.

2. Selected ionospheric conditions

In order to comprehensively evaluate the accuracy of locally adapted NeQuick 2 model in middle latitudes, days with different ionospheric conditions were selected from the period between January 1, 2011 and September 30, 2015. Selection had to include periods of quiet and disturbed geomagnetic field, four seasons of the year, and different levels of solar activity.

The solar activity is usually represented by 10.7 cm wavelength solar radio flux called *F10.7* index and measured in Solar Flux Units (SFU), with 1 SFU = 10^{-22} $\mathrm{Wm^{-2}Hz^{-1}}$ (Tapping, 2013). The *F10.7* indices are made publicly available by Analytical Graphics, Inc. (2016). Chosen years mostly overlapped with the active part of the 24th solar 11-year cycle, except at the very beginning. Therefore, days with the lowest *F10.7* index (lower than 80 SFU), appearing in January of 2011, represented inactive to moderately active Sun. Days in February 2014, with the highest *F10.7* index (higher than 180 SFU), represented the peak of the solar cycle. It should be noted that the current solar cycle 24 is less active than the preceding cycles.

Ionospheric seasonality was taken into account by choosing days of each season (winter, vernal equinox, summer and autumnal equinox) from each of the observed years. Selection of days was based on analysis of annual