Ionospheric correction based on NeQuick 2 model adaptation to Global Ionospheric Maps

Xiao Yu [1], Weimin Zhen [2], Ming Ou [3] and Dun Liu [4]

[1]Wuhan University, Wuhan 430079, P. R. China. E-mail: earings322@163.com

[2] CRIRP (China Research institute of Radiowave Propagation), Qingdao 266107, P. R. China.
E-mail: crirp_zwm@163.com

[3] Wuhan University, Wuhan 430079, P. R. China. E-mail: Ohm22@163.com

[4] CRIRP, Qingdao 266107, P. R. China. E-mail: GNSS2001@163.com

Abstract

Global Ionospheric Maps (GIMs), computed by Center for Orbit Determination in Europe (CODE) during a period longer than an entire 11 years solar activity cycle, have been used as the primary source of data to provide global ionospheric corrections for possible single frequency positioning applications. The aim of the investigation is to assess the performance of NeQuick 2 model in providing global total electron content (TEC) prediction after ingesting GIMs data from previous day(s). The results show good performance of the GIMs-driven-NeQuick results with average cumulative distribution function (CDF) of vTEC error not to exceed 5 TECU or 20% (zi_{20}) near 76.70%. The performance of GIMs-driven-NeQuick also presents variability with solar activity, and behaves better during low solar activity years. There are also seasonal trends of the performance. Generally, zi_{20} values are bigger in summer and winter and lower in spring and autumn. The differences between in summer and in winter are quite small. And as more measurements from earlier days are used, the accuracies may decrease.

1. Introduction

One of the major error sources in Global Navigation Satellite System (GNSS) positioning is ionosphere refraction which causes signal propagation delay and advances depending on the carrier frequency f [Hz] and on the ionospheric TEC (Unit: TECU, 1TECU = 1×10^{16}el/m^2). For code measurements, the consequent pseudorange error Ig [m] can be described as a first approximation by:

$$I_g = \frac{40.3}{f^2} \times sTEC \tag{1}$$

Here, the slant TEC is defined as the integral of the electron density along the path from the satellite transmitter to the ground receiver, and can be converted to equivalent vertical TEC (vTEC) by an appropriate mapping function. As it is well known, the GNSS single-frequency receivers have to compensate for the unwanted term Ig, before solving the navigation equations. In this case an explicit estimate of the TEC is usually obtained by means of an ionospheric model.

Until recently, several models that can be used to take into account this ionospheric term have been developed and still are main topics for navigation application. The GPS Ionospheric Correction Algorithm (ICA) or Klobuchar model [1], designed on the basis of the Bent model, uses 8 broadcast coefficients from the navigation message to compute vTEC. Assuming a thin ionosphere, slant TEC is then computed and converted to time delay. The model is supposed to provide a 50% root mean square (RMS) correction. The Galileo ICA can be described as follows: (1) The sensor stations observe slant TEC for 24 hours and optimize effective ionization parameter for NeQuick to match observations; (2) The satellite transmits effective ionization parameter in navigation message (using 3 broadcast coefficients); (3) The user receiver calculates slant TEC using NeQuick with broadcast ionization parameter and correct for ionospheric delay at frequency in question [2].

In the present work, NeQuick 2, which is the new version of NeQuick model [3] and quite different from the Galileo NeQuick, has been used to generate the ionospheric correction coefficients in a Galileo-like mode. GIMs have been used as the primary source of data to investigate the ability of NeQuick to accommodate TEC measurements and to evaluate the model capabilities in providing global daily TEC predictions after ingesting measured values from the previous day(s).

2. Data ingestion technique and dataset

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NeQuick 2 includes major changes in the representation of the topside [4] and in the bottomside [5] of the ionosphere and calculates the ionospheric electron density (and TEC) depending on different parameters such as location, time of the day, season, solar or geomagnetic activity, using solar activity indices as standard input. However, these indices are based on solar observation and do not necessarily account perfectly for the solar activity in EUV radiations inducing the ionization in the Earth atmosphere. In order to improve the model performance and prediction capabilities, data ingestion and assimilation techniques have been used, which replace standard solar activity indices with different "effective" indices to allow adapting a model to a specific data set [6].

In this study, CODE GIMs are chosen as measured values both for convenience and their high qualities [7]. At CODE, the vTEC is modeled in a solar-geomagnetic reference frame using a spherical harmonics expansion, and piece-wise linear functions are used for representation in the time domain. Daily DCB for all GPS satellites and ground stations are estimated as constant values. The vTEC grids are along the geographical latitude and longitude, which range from 87.5ºS to 87.5ºN and 180ºW to 180ºE. The grid intervals are 2.5º and 5º respectively. The maps are supported every 2 hours. The period of data used in this paper spans from 28 March 1998 to 31 December 2011, and the dataset is perfectly complete.

3. Ionospheric correction algorithm

The ionospheric correction algorithm is based on NeQuick 2 adaptation to GIMs dataset. To generate the Galileo-like ionospheric correction parameters, the following procedure should be considered. First of all, NeQuick 2 is optimized as a function of the daily effective ionization level (Az) to the measured vTEC values. Following the Galileo ICA, Az is applicable for a period of 24 hours. At a given grid point, the root mean square of TEC differences, defined as residual TEC errors, ΔTEC are calculated:

$$\Delta TEC = \sqrt{\left(\sum_{i=1}^{N}\left(TEC_{observed} - TEC_{modeled}(F10.7)\right)^2\right) \Big/ N} \tag{2}$$

Here, N is the number of individual observations during the day and equals to 12, $TEC_{observed}$ and $TEC_{modeled}$ are the TEC observations given by GIMs and TEC output by NeQuick 2, respectively. As an example, Fig. 1 illustrates how ΔTEC changes versus F10.7 at a grid point (45ºN, 0ºE) for a given day (30 May 2004). It can be seen that ΔTEC values decrease from 8.43 TECU to 2.46 TECU when F10.7 increases from 63 to 115.3. By contrast, as F10.7 increases from 115.3 to 193, ΔTEC increases from 2.46 TECU to 15.69 TECU. Thus ΔTEC minimizes when F10.7 approaches to 115.3, and the daily Az equals to 115.3.

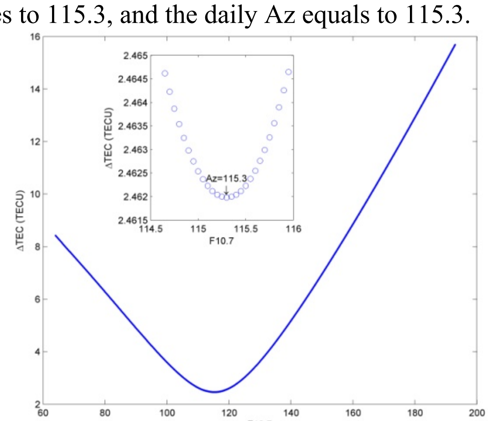

Fig. 1 ΔTEC versus F10.7 at (45ºN, 0ºE), for 30 May 2004

Repeating the procedures described above, global Az and residual TEC errors can be obtained. Since the polar region (extending from about 60º northward and southward of the Equator to polar caps) exhibits feature cannot be physically true (highest and highly variable Az values, but the lowest residual TEC errors), we only consider data sets having the geographical latitude between 60ºS and 60ºN.

Even if it is not a real ionospheric parameter, Az exhibits variations with geographic location. To describe the mixed dependence of Az on the geomagnetic field and geographical latitude, modified dip latitude (MODIP, [8]) μ [°] defined as follows has been used.

$$\tan \mu = \frac{I}{\sqrt{\cos \phi}} \tag{3}$$

Here, I and ϕ denote the geomagnetic dip and the geographic latitude, respectively. And μ will be computed using the IGRF (or DGRF) models. After the daily available Az values for all the 3528 grid points (72 and 49 grid points along the geographical longitude and latitude, respectively) are calculated and collected, Az can be regressed as a second order polynomial function of MODIP:

$$Az = a_0 + a_1\mu + a_2\mu^2 \tag{4}$$

In the following, the three coefficients a_0, a_1 and a_2 will be calculated after an optimization procedure based on the global observations, and $Az_{modeled}$ will be computed by substituting a_0, a_1, a_2 and μ values into Equ.(4). Fig.2 gives an example of Az and $Az_{modeled}$ values versus MODIP for 6 April, 2004. The blue dots and red circles denote Az and $Az_{modeled}$ respectively. It is obvious that for a fixed MODIP, there is a spread of Az, and the peak-to-peak values of Az can reach up to 50 (near 40ºS), and we attribute it to the longitudinal effect, which is not included in the definition of MODIP (seen in Equ. 3). Thus we suppose that using a single value to characterize them will not be enough and will induce some errors. The fact that global peak-to-peak values of Az can come up to 100 clearly reflect NeQuick itself cannot fully reproduce the detailed characteristics of global daily TEC distribution in particular with the current adaptation technique.

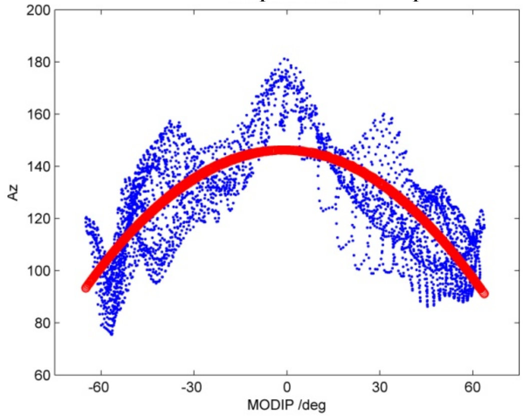

Fig.2 Az and $Az_{modeled}$ versus MODIP

Then GIMs-driven-NeQuick results can be obtained by using $Az_{modeled}$ as NeQuick 2 input. Taking the GIMs as reference, the statistical TEC difference (errors) will be analyzed in order to assess the performance of NeQuick 2 in reproducing global TEC distribution. Likewise, if 12 GIMs of the previous day are used as ingested dataset and GIMs of the current day as reference, the performance of NeQuick 2 in ionospheric correction (proportional to TEC) predictions can be obtained.

4. Assessment tools and results

According to its specification, Galileo ionospheric pseudorange error is not to exceed 20 TECU or 30%, whichever is larger [2]. Considering the situations we considering here are the most ideal situations, corresponding to zero measurement errors and even distribution of TEC measurements, we take a more rigorous criteria to do the assessment (the error is not to exceed 5 TECU or 20%, whichever is larger). Since the fact that the time delay on GNSS signals is proportional to TEC values makes the necessity of ionospheric correction not as impending at nighttime as at daytime, the nighttime values (LT>18 or LT<6) are discarded.

Then we compute the cumulative distribution function (CDF) of TEC errors meet the specification (not to exceed 5 TECU or 20%) for each day using the previous day GIMs, and time series of this parameter (denoted as zi_{20}) are given in Fig.3. It can be argued that in general the performance of GIMs-driven-NeQuick model in predicting global TEC distribution is quite good. Few values vary below 50%, and the mean of zi_{20} is 76.70%. The performance of GIMs-driven-NeQuick also presents variability with solar activity, and behaves better during low solar activity years when the error not to exceed 5 TECU can be easily satisfied.

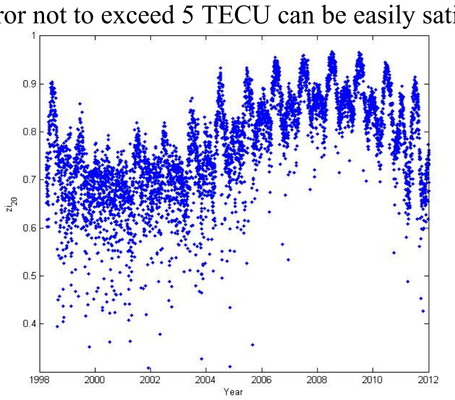

Fig.3 Time series of zi_{20}, using the previous day Az

Considering the situation that in some applications we cannot get GIMs or other measurements the day before prediction, the possibility to use measurements taken at earlier time may have some practical meanings and are investigated. In this study, we carry out a test study of the ionospheric correction based on NeQuick 2 ingesting GIMs data of the current day, during 1 to 3 days before, during 1 to 5 days before, respectively and the mean values of zi_{20} approach to 78.65%, 76.03% and 75.33%, respectively. Thus for forecasting purpose, historical data older than 5 days should not be considered. To study how the performance of ionospheric correction based on the NeQuick 2 model adaptation to previous day(s) CODE GIMs changes with solar activity levels and seasons, the mean values of zi_{20}(%) are computed and the results are listed in table 1. According to annual mean F10.7 indices, the dataset are divided into 3 groups (left): Low Solar Activity (LSA, year 2005 to 2010), Medium Solar Activity (MSA, year 1998, 2003, 2004 and 2011) and High Solar Activity (HAS, year 1999 to 2002). To study its dependence on seasons, the dataset are divided into 4 seasons (right): northern (southern) hemisphere spring (autumn) (February to April), northern (southern) hemisphere summer (winter) (May to July), northern (southern) hemisphere autumn (spring) (August to October) and northern (southern) hemisphere winter (summer) (November, December and January). It is obvious that performance of NeQuick adapted to GIMs also presents variability with solar activity levels, and behaves better during low solar activity years. There are also seasonal trends of the performance. Generally, zi_{20} values are bigger in summer and winter and lower in spring and autumn. The differences between in summer and in winter are quite small.

TABLE 1

Trends of zi_{20}(%) mean values with solar activity (left) and seasons (right)

Zi_{20}(%)	LSA	MSA	HSA
Current day	84.84	73.43	67.95
Previous day	84.48	72.69	66.93
1to3days before	84.28	72.28	66.44
1to5days before	84.10	71.85	65.93

zi_{20}(%)	Spring	Summer	Autumn	Winter
Current day	76.83	80.0	75.94	81.02
Previous day	75.16	77.76	73.99	79.24
1 to 3days before	74.63	76.98	73.27	78.61
1to 5 days before	74.02	76.24	72.46	77.96

5. Conclusion

In this paper, we carry out a study of ionospheric modeling based on NeQuick 2 adaptation to CODE GIMs, which spans over 13 years have been used. The primary aim of this investigation is to assess the performance of NeQuick 2 model in providing global TEC predictions after ingesting measured values, such as previous day(s) GIMs data. The main conclusions are as follows: (1) In general, the performance of NeQuick adapted to previous day GIMs is quite good, with average cumulative distribution function (CDF) of vTEC error not to exceed 5 TECU or 20% near 76.7%. (2) The performance of NeQuick adapted to GIMs also presents variability with solar activity, and behaves better during low solar activity years. (3) There are also seasonal trends of the performance. Generally, zi_{20} values are bigger in summer and winter and lower in spring and autumn. The differences between in summer and in winter are quite small. (4) As more measurements from earlier days are used, the accuracies may decrease.

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