Ionospheric Models for GNSS Single Frequency Range Delay Corrections

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ABSTRACT
The paper explains briefly the effect of the ionosphere on the operation of GNSS in terms of the range delay introduced by the presence of the ionization, when the satellite signals are used to calculate the position of a user that receives the signals. A description of the two ionospheric models used by the GPS and in future GALILEO to correct such delay is given. A comparison of the results obtained by the two operational models is provided.
Key words: GNSS, GPS, GALILEO, ionospheric model, total electron content.

RESUMEN
El trabajo explica brevemente el efecto de la ionosfera sobre la operación de los Sistemas Satelitales Globales de Navegación (GNSS) en relación al retardo introducido por la presencia de la ionización, cuando se utilizan las señales de satélite para calcular la posición de un usuario que recibe las señales. Se describen los dos modelos utilizados por el GPS y el futuro GALILEO a tal fin. Se comparan los resultados obtenidos por los dos modelos operativos.
Palabras clave: GNSS, GPS, GALILEO, modelo ionosférico, contenido electrónico total.

1. INTRODUCTION

Global Navigation Satellite Systems (GNSS) consist of a network of satellites in medium Earth orbit that transmit radio signals in the L1 and L2 bands of the spectrum that are used to determine the position of a user that receives the signals. The first operational GNSS is the Global Positioning System developed by the USA. The second operational system is the Russian one called GLONASS originally deployed by the former Soviet Union. The international civilian community can use both systems although the United States Department of Defence and the Russian Space Forces operate respectively these systems. GALILEO is a third system planned by the European Union. In addition, a number of Satellite Based Augmentation Systems (SBAS) are in operation or will be soon operational. They provide wide-area or regional augmentation through the use of additional satellite-broadcast messages. Such systems are commonly composed of multiple ground stations that take measurements of the GNSS satellites signals determining environmental factors that may impact on the signal received by the users. Using these measurements, information messages are created and sent to one or more geostationary satellites for broadcast to the end users.

With information about the ranges to four satellites and the location of the satellite when the signal was sent, a receiver can compute its own three-dimensional position. A clock synchronized to the satellites clock is required in order to compute ranges from these signals. Thus, the receiver uses four satellites to compute latitude, longitude, altitude, and time. A series of factors can degrade the GNSS signal and affect the accuracy of the computation. The most important factor is the presence of the ionosphere.

The largest effect of the ionosphere on GNSS positioning is the group time delay that a radio signal experiences travelling though the ionosphere. The group time delay is essentially proportional to the total electron content along the path of the radio wave propagation and inversely proportional to the square of its frequency:

$$\Delta t = \frac{(K \cdot TEC)}{f^2} \tag{1}$$

where:

Δt = group delay time [s]
K = constant = 1.34 x 10^{-3} [m^2s^{-1}]
TEC = total electron content along the path (measured in TEC units where 1TECu =10^{16} m^{-2})
f = frequency [MHz]

Ionosphere correction models are required to correct the time delay or its equivalent range delay introduced by the ionosphere. Dual frequency (L1 and L2) receivers can be used to remove this effect to first order. However, such receivers are more susceptible than single frequency receivers to loss of lock caused by ionosphere scintillation.

Steep electron density gradients associated with critical geographic regions like the region of the trough (middle-high latitudes) or the equatorial region may also cause problems to regional SBAS operation.

An ionosphere model to be used operationally to correct the range delay should have the following main characteristics:

- It should be reasonably simple in its formulation to limit the computer time needed for the calculation of the relevant total electron content values along the given path of radio wave propagation.
- It should be realistic in representing the global ionosphere behaviour.

- It should be able to be adapted to the actual conditions of the ionosphere by means of a limited information (limited number of bits) to be broadcast at a certain time interval in the navigation message of the GNSS.

Two models appear to be usable for operational function by a GNSS in the single frequency mode. The ICA model (Klobuchar, 1987) used for ionospheric delay correction by the GPS and the NeQuick model, an evolution of previous models (Radicella and Leitinger, 2001), to be used by the GALILEO system with the same purpose.

2. THE GPS MODEL FOR IONOSPHERIC CORRECTIONS

GPS uses a simple ionospheric model, the Ionospheric Correction Algorithm (ICA), which provides a representation of the mean vertical delay at L1, for given geomagnetic location and local time (Klobuchar, 1987). The algorithm is essentially based on the Bent model (Llewellyn and Bent 1973) which gives the ionosphere electron density as a function of latitude, longitude, time, season, and solar radio flux. ICA is a TEC model, designed to minimize user computational complexity with the goal of a 50% rms ionosphere vertical delay error correction.

The diurnal variation of vertical ionospheric delay is modelled by a cosine function, with varying amplitude and period, depending on the geomagnetic latitude. The phase of the cosine is fixed to 14 LT. During nighttime the vertical ionospheric delay is approximated to a constant value: 5 ns.

The dependency on geomagnetic latitude Φ_m is given by third order polynomials, which coefficients α_n and β_n (eight in total) are broadcast in GPS navigation message.

The cosine function argument is:

$$x = \frac{2\pi\,(t - 50400)}{\sum_{n=0}^{3} \beta_n \Phi_m^n} \tag{2}$$

where β_n coefficients control the variation of the period as function of the geomagnetic latitude. α_n coefficients control the amplitude of the ionospheric delay:

$$\sum_{n=0}^{3} \alpha_n \Phi_m^n \cos x \tag{3}$$

Therefore to compute the ionospheric delay T_{iono} it is necessary to add to the night-time constant vertical delay the diurnal variation given by (3) expressed by its Taylor expansions. The result is multiplied times the obliquity factor:

$$F = sec\left(arcsin\ (0.94792cos\theta)\right) \simeq 1 + 2\left(\frac{96° - \theta}{90°}\right)^3 \tag{4}$$

thus:

$$T_{iono} = F\left(5\ x\ 10^{-9} + \sum_{n=0}^{3} \alpha_n \Phi_m^n \left(1 - \frac{x^2}{2} + \frac{x^4}{24}\right)\right) \tag{5}$$

The transition from day to night is controlled by |x| ≥ 1.75. When this value is exceeded the ionospheric delay becomes:

$$T_{iono} = 5\ x\ 10^{-9}\ F \tag{6}$$

The ionospheric delay obtained by ICA algorithm is expressed in seconds.

Operationally the eight α_n and β_n coefficients broadcast in the navigation message are updated approximately every week.

As an example, in Figure 1 a vertical TEC map obtained with ICA is shown.

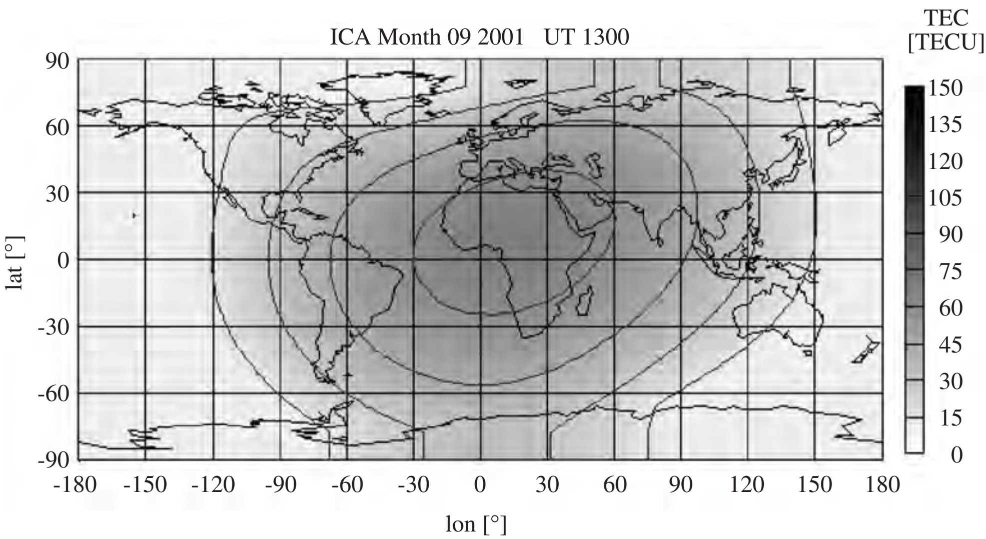

Figure 1.- Global map of vertical TEC using ICA.

3. THE NEQUICK MODEL

NeQuick (Hochegger et al., 2000; Radicella and Leitinger, 2001) is a three dimensional and time dependent ionospheric electron density model 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 of the University of Graz, Austria. It is has been created on the basis of the analytical model by Di Giovanni - Radicella (DGR) (Di Giovanni and Radicella, 1990), later improved by Radicella and Zhang, (1995). It gives an analytical representation of the vertical profile of electron density, continuous with continuous first and second derivatives. It is a quick-run model particularly tailored for trans-ionospheric applications that allows to calculate the electron concentration at any given location in the ionosphere and thus the Total Electron Content (TEC) along any ground-to-satellite ray-path by means of numerical integration. The NeQuick model has been adopted by the International Telecommunication Union, Radiocommunication Sector, ITU-R Recommendation P. 531-7 (ITU, 2003) as a suitable method for TEC modeling.

Taking advantage of the increasing amount of available data, the model formulation is continuously updated to improve NeQuick capabilities to provide representations of the ionosphere at global scales. A new version of the model, NeQuick 2, has been released recently and has been described in full details by Nava et al. (2008).

The vertical electron density profile is given by a sum of Epstein layers, first introduced by (Rawer, 1963):

$$N_{Epstein}(h, hm, Nm, B) = \frac{4Nm}{\left(1 + exp\left(\frac{h\text{-}hm}{B}\right)\right)^2} exp\left(\frac{h - hm}{B}\right) \qquad (7)$$

where Nm [m^{-3}] and hm [km] are the electron density and height of the layer maximum and [km] is the layer thickness parameter.

Being NmE = 0.124 (foE)^2, NmF1 = 0.124 (foF1)^2, NmF2 = 0.124 (foF2)^2 the E, F1 and F2 layer peak electron densities (in 10^{11}m^{-3}), hmE, hmF1, hmF2 peak heights (in km) and BE, B1, B2 the E, F1 and F2 layer thickness parameters (in km), the bottomside of the NeQuick 2 can be expressed as a sum of semi-Epstein layers as follows:

$$N_{bot}(h) = N_E(h) + N_{F1}(h) + N_{F2}(h) \qquad (8)$$

where:

$$N_E(h) = \frac{4Nm * E}{\left(1 + exp\left(\frac{h\text{-}hmE}{BE}\,\xi(h)\right)\right)^2} exp\left(\frac{h - hmE}{BE}\,\xi(h)\right) \qquad (9)$$

$$N_E(h) = \frac{4Nm * F1}{\left(1 + exp\left(\frac{h\text{-}hmF1}{B1}\xi(h)\right)\right)^2} exp\left(\frac{h - hmF1}{B_1}\xi(h)\right) \tag{10}$$

$$N_E(h) = \frac{4Nm * F2}{\left(1 + exp\left(\frac{h\text{-}hmF2}{B2}\xi(h)\right)\right)^2} exp\left(\frac{h - hmF2}{B_2}\xi(h)\right) \tag{11}$$

with

$$Nm * E = NmE - N_{F1}(hmE) - N_{F2}(hmE) \tag{12}$$

$$Nm * F1 = NmF1 - N_E(hmF1) - N_{F2}(hmF1) \tag{13}$$

and

$$\xi(h) = exp\left(\frac{10}{1 + 1\,|h - hmF2|}\right) \tag{14}$$

is a function that ensures a ”fading out” of the E and F1 layers in the vicinity of the F2 layer peak in order to avoid secondary maxima around hmF2. In accordance to the behaviour of the F1 layer, the expression (12) and (13) can be slightly modified.

The thickness parameters take different values for the bottomside and for the topside of each layer (BE_{bot} and BE_{top} for the E layer, $B1_{bot}$ and $B1_{top}$ for the F1 layer, $B2_{bot}$ for the F layer).

The model topside is represented by a semi-Epstein layer with a height dependent thickness parameter H:

$$N(h) = \frac{4NmF2}{(1 + exp(z))^2} exp(z) \tag{15}$$

with

$$z = \frac{h - hmF2}{H} \tag{16}$$

where:

$$H = kB2_{bot}\left[1 + \frac{rg\,(h - hmF2)}{rkB2_{bot} + g\,(h - hmF2)}\right] \qquad (17)$$

with constant values $r = 100$ and $g = 0.125$.

The parameter k, which appears in equation (17), is given by (Coïsson et al, 2006):

$$k = 3.22 - 0.0538foF2 - 0.00664hmF2 + 0.13\,\frac{hmF2}{B2_{bot}} + 0.00257R12 \qquad (18)$$

It has to be noted that the present version of the International Reference Ionosphere model of electron density, IRI 2007, has introduced as the default option of its ionosphere topside description the NeQuick2 topside (http://omniweb.gsfc.nasa.gov/vitmo/iri_vitmo.html).

Since the ionosphere is mostly controlled by the Earth magnetic field, to model the global distribution of electron density various geomagnetic coordinates are used. NeQuick uses modip μ, which was first introduced by (Rawer, 1963):

$$\tan \mu = \frac{I}{\sqrt{\cos\varphi}} \qquad (19)$$

in which I is magnetic inclination at 300 km and φ is latitude of the considered location. NeQuick 2 uses a grid of modip values. To compute the modip value in a point at latitude φ and longitude λ, a third order interpolation is applied using the surroundings grid values.

As an example, in Figure 2 a global vertical TEC map computed with NeQuick 2 is shown.

NeQuick model has been utilized, among other uses, by the European Geostationary Navigation Overlay Service (EGNOS) project of the European Space Agency for system assessment analysis and has been implemented in the Global Ionospheric Scintillation Model (GISM) to calculate the background ionosphere (Beniguel, 2004). In addition NeQuick model can be used for accurate specification of the ionosphere by ingesting experimental data obtained from the International GPS Service and the ionosonde global network (Nava et al., 2006).

4. NEQUICK MODEL FOR GALILEO

For its use in the operational mode by the GALILEO system the model will be driven by an "effective ionisation level" Az, valid for the whole world and applicable for a period of typically 24 hours. Az is defined as follows:

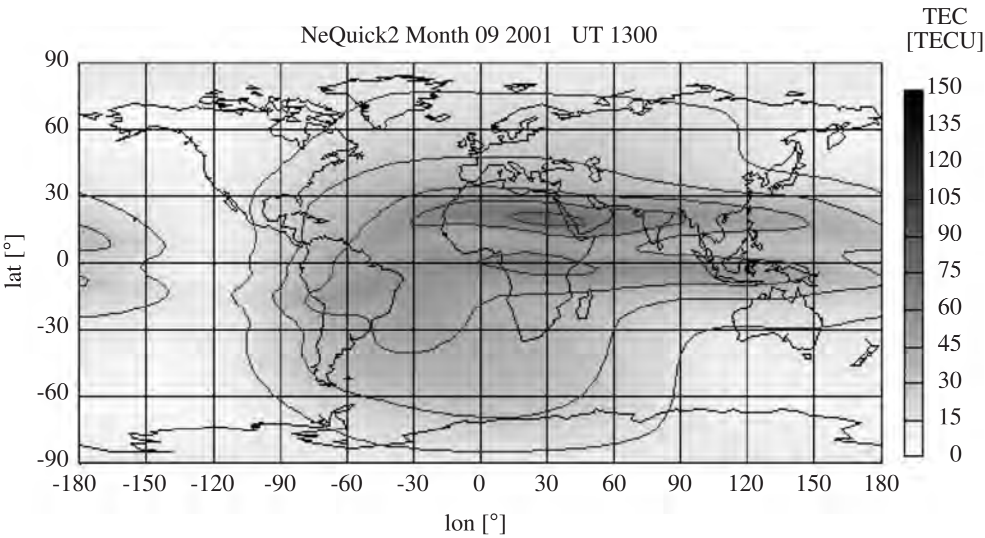

Figure 2.- Global map of vertical TEC using NeQuick 2 model.

$$Az\ (\mu) = a_0 + a_1\mu + a_2\mu^2 \tag{19}$$

where μ is the modip and the coefficients a_0, a_1, a_2 are broadcast to the user to allow Az calculation at any wanted location. The computed Az values are formally used as solar flux input values for the NeQuick model and they can be interpreted as effective solar flux values that varies with modip. Therefore the electron density values along any given receiver-to-satellite ray-path and the corresponding TEC can be estimated.

The Az coefficients broadcast and used for a given day are computed at system level using TEC data of the previous day.

More in detail, to calculate the a_0, a_1, a_2 coefficients the following steps are required:

- Slant TEC values from each monitoring station for each satellite in view above a certain elevation mask angle for a given length of time are used. It is assumed that at least 20 Galileo monitoring stations globally distributed are available for providing slant TEC values.
- Electron density along each path is estimated and integrated using the NeQuick model to obtain computed slant values as a function of Az. The model slant TEC for given consecutive satellite-station paths are computed.
- The sum of squares "observed minus computed" will be minimized as a function of *Az* using numerical techniques for the automatic search of the minimum (e.g. Brent method, [Brent, 1973]).

- The value of Az that minimizes the departure between observed and modelled first differences of un-calibrated slant TEC is determined for a given interval of time (24 hours) for each monitoring station.
- From the calculated Az at different monitoring stations a global Az as a function of modip using a 2nd degree polynomial determining a set of 3 coefficients (a_0, a_1, a_2) is determined.

5. PERFORMANCE OF THE OPERATIONAL MODELS

A series of tests have been done to evaluate the performance of the two models that are used (ICA GPS model) or would be used (NeQuick) for GNSS single frequency operation. These tests have been done in terms of slant TEC mis-modelling that is equivalent to single path range errors. The mis-modelling is defined as the difference between an experimental and its corresponding modelled slant TEC.

For the simulation of operational use of NeQuick model, experimental slant TEC values obtained from a set of worldwide distributed "monitoring" stations in a period of 24 hours are used to compute the parameters a_0, a_1, a_2 to estimate Az parameter for the given day. The locations of the "monitoring" (IGS) stations are shown in Figure 3.

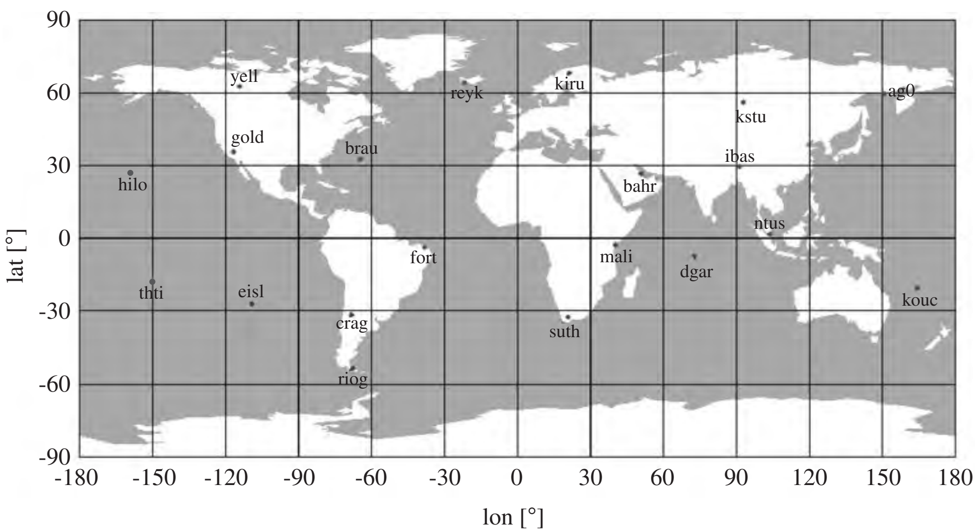

Figure 3.- Location of the "monitoring" stations.

These coefficients are used during the following day to drive the NeQuick 2 model and compute the slant TEC along any satellite to receiver ray-path. A specific NeQuick program adaptation has been realized for that purpose.

In the case of ICA, the GPS broadcast coefficients have been used to compute the slant TEC on the same satellite to receiver links.

To perform a global analysis of the models performance, a set of 27 test IGS stations homogeneously distributed around the World has been selected. They have been chosen to cover all modip regions; their geographical distribution is shown in Figure 4, where lines of equal modip are also drawn. This selection guarantees that the statistical analysis does not suffer because of the uneven distribution of the stations.

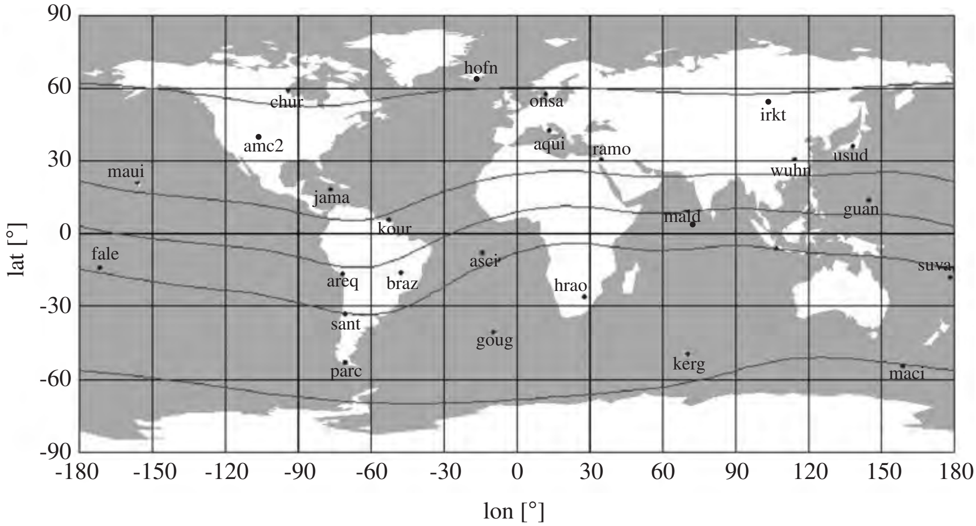

Figure 4.- Location of the test stations. Lines of equal modip are drawn at -60°, -30°, 0°, 30°, 60°.

Daily statistics were performed extracting the 65 and 95 percentiles of the cumulative distribution of the absolute value of the mis-modelling available in the test stations during one day.

A total of 8000 to 11000 values of slant TEC values were compared for each day. The results are shown in Figure 5 and Figure 6. It appears that in almost all cases NeQuick 2 mis-modelling is smaller than the ICA one, reflecting the more realistic global behaviour of NeQuick 2.

In the case of 65-percentiles (Figure 5), NeQuick 2 absolute mis-modelling values are in general lower than 20 TEC units (except in very few cases) and the corresponding ICA values are 5-10 TECu greater than the NeQuick ones. The NeQuick 2 also exhibits a smaller day-to-day variation indicating a more stable behaviour. The higher values are found for both models in April.

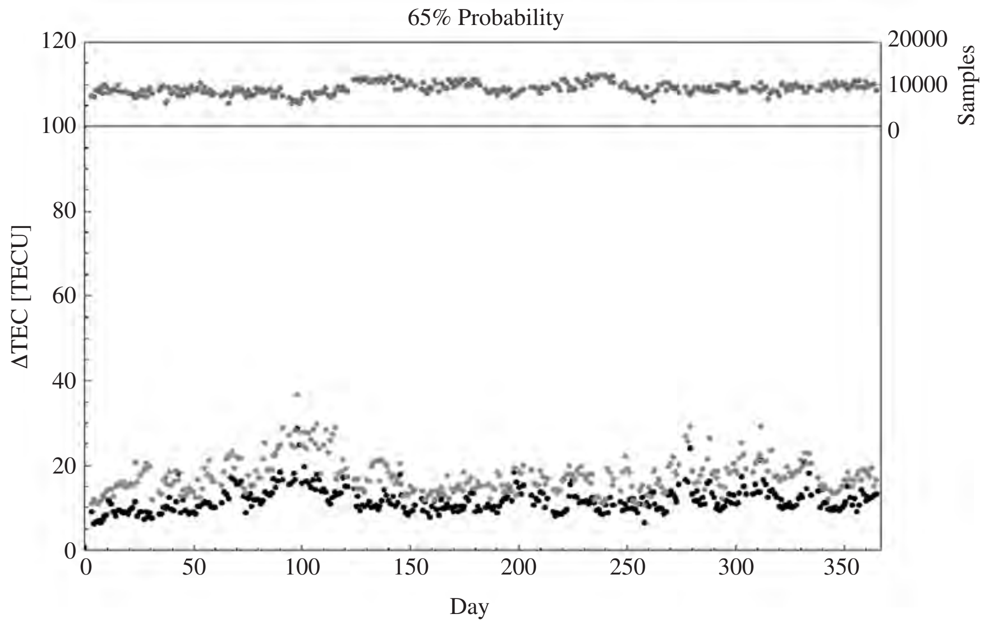

Figure 5.- Year 2000 daily 65 percentile of the absolute values of the mis-modellings for NeQuick 2 (black) and ICA-Klobuchar (grey).

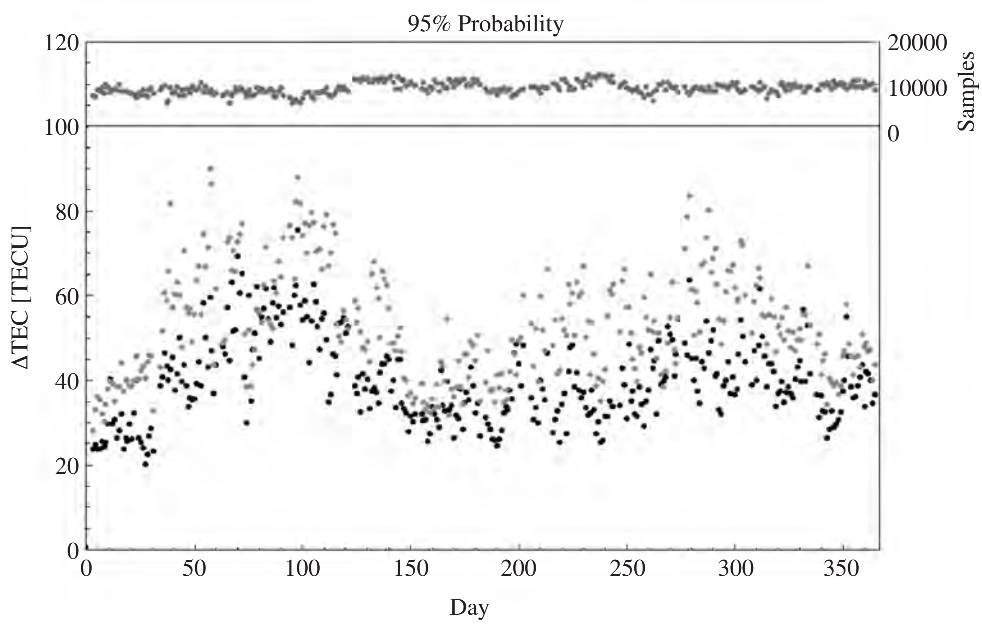

Figure 6.- Year 2000 daily 95 percentile of the absolute values of the mis-modellings for NeQuick 2 (black) and ICA-Klobuchar (grey).

The 95-percentile (Figure 6) shows a larger day-to-day variability of the mis-modelling particularly during equinoctial months. Again NeQuick 2 absolute mis-modelling values are smaller than ICA ones, with values ranging from 20 to 70 TEC units. In general the ICA mis-modelling exceeds the corresponding NeQuick 2 one by about 20 TEC units or more. Larger spreading and larger day-to-day variations are also found for ICA. For both models it appears that during solstice months (January, June, July) the 95-percentiles are lower and the spreading of values is smaller than during equinoctial months (March, April, September and October).

6. AKNOWLEGEMENTS

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