Towards an Improved Single-Frequency Ionospheric Correction: Focus on Mid-Latitudes[1]

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ABSTRACT

The **modelling of the Total Electron Content (TEC)** plays an important role in global satellite navigation systems (GNSS) accuracy, especially for **single frequency receivers**, the most common ones constituting the mass market. For the latter and in the framework of Galileo, the **NeQuick model** has been chosen for correcting the ionospheric error contribution and will be integrated into a global algorithm providing the users with daily updated information.

In order to reach the ionosphere error correction level objective, the model itself as well as its use for Galileo are **investigated**. In our comparison process, we take advantage of various ionosphere data from several European stations (Dourbes in Belgium, El Arenosillo and Roquetes in Spain) where **ionosonde and GPS TEC data** are available for different solar activity levels. These data allow us to study NeQuick representation of the ionosphere at **mid-latitudes**. Constraining the model with ionosonde measurements, we investigate the difference between GPS-derived vertical TEC and corresponding values from NeQuick for a **high solar activity level** (year 2002). With this approach, we reach **residual errors of less than 20% in standard deviation**. We especially highlight the **improvements from the latest (second) version** of NeQuick and show the **critical importance of the topside** formulation. Finally we analyse the model residual errors when using an **ingestion** scheme for Dourbes station. We compute daily effective values of solar flux adapting NeQuick slant TEC values to GPS-derived ones and we show that **residual errors** in vertical TEC are **partially resorbed** thanks to this technique.

1 INTRODUCTION

The ***ionosphere*** *is defined, for our purposes, as that part of the upper atmosphere where sufficient ionization can exist to affect the propagation of radio waves [1, Chap. 1].* This definition reveals particularly well the intrinsic link binding the ionosphere to its effects and the context of this study. Indeed this part of the atmosphere extending between 50 and several thousand kilometres from earth surface produces different effects on Global Navigation Satellite Systems (GNSS) [2]. The major influence from its intrinsic electron concentration N_e $[electrons\ m^{-3}]$ concerns the time of flight of navigation signals depending on their frequency f $[Hz]$ and on the total content in free electrons of the ionosphere. For code measurements, the consecutive **pseudorange error** I_g $[m]$ is obtained as follows at first approximation.

$$I_g = \frac{40.3}{f^2} \int_{sat.}^{rec.} N_e \, ds = \frac{40.3}{f^2} sTEC \tag{1}$$

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[1] Find material about this paper on `http://orbi.ulg.ac.be/handle/2268/1551`

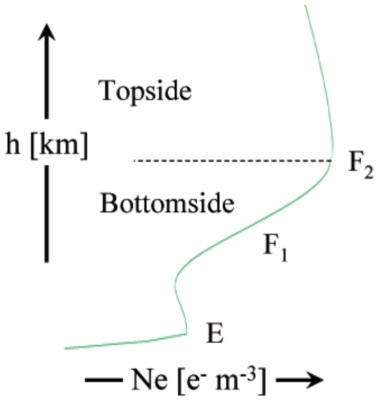

Fig. 1. Electron density profile and characteristic regions

This slant *"total electron content"* (sTEC) is defined as the integral of the electron density on the path between the satellite and the receiver. Its units are $[electrons\ m^{-2}]$ or more generally TEC units $[TECu = 10^{16}\ el.m^{-2}]$, one $TECu$ inducing an error of 0.16 m for the L_1 carrier (1575.42 MHz) and it can be converted to vertical TEC (vTEC) by means of a mapping function. As every ionospheric parameter, the value of TEC depends on different factors such as location, time of the day, season, solar or geomagnetic activity.

TEC modelling reveals itself of first importance especially for *single frequency receivers*, the most common ones constituting the mass market, but also for multiple-frequency devices. The latest will indeed comprise a *fallback mode* in single frequency within the framework of critical applications such as civil aviation where the level of precision must be guaranteed in all circumstances. For Galileo single frequency users, the ionospheric error correction algorithm uses the **NeQuick** model to compute TEC [3, 4]. Understanding its *weaknesses and evolutions* and *validating* its results constitutes then a task of prime order to reach the best correction level. Therefore *different situations* have to be considered: different latitude regions (space conditions), different hours, seasons and years (time conditions) and specific phenomena occurrence (magnetic storms, Travelling Ionospheric Disturbances - TIDs). In addition the results can be compared to *different data sets* among which GPS slant or vertical TEC measurements, Global Ionospheric Maps, ionosonde profiles, topside soundings. We chose as a first step to investigate NeQuick performance at mid-latitudes using ionosonde and GPS TEC data.

2 TOOLS AND METHOD

2.1 NeQuick Model

NeQuick belongs to the "DGR family" of ionospheric models known as "**profilers**" [5, 6]. They indeed fit analytical functions on a set of anchor points, namely the E, F_1 and F_2 layer peaks, to represent these principal ionospheric layers and compute the electron density profile (cf. fig. 1). NeQuick is the simplest one and was adopted by the ITU-R recommendation for TEC modelling [7]. The NeQuick model is divided into two regions [8]: the *bottomside*, up to the F_2-layer peak, consists of a sum of five semi-Epstein layers[2] [9] and the *topside* is described by means of an only sixth semi-Epstein layer with a height-dependent thickness parameter.

To compute the parameters for the Epstein layers[3], the thickness parameters B^L_{bot} and B^L_{top} and the anchor points coordinates i.e. peaks electron density NmL and height hmL, NeQuick employs the *ionosonde parameters*, f_oE, f_oF_1, f_oF_2 and $M(3000)F_2$. These critical frequencies and transmission factor are themselves obtained from empirical equations among which the CCIR maps [10] for the F_2 characteristics[4] so that a monthly median situation is represented. However the power of NeQuick consists in its ability to accommodate other sources of data for these parameters e.g. measured values.

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[2] The prefix "semi" means that different thickness parameters are used below and above the layer peak.

[3] L stands for the layer index which possible values are E, F_1 and F_2.

[4] Note that NeQuick f_oE and f_oF_1 should be referred to as *effective* critical frequencies as their definition does not correspond exactly to the cited reference ITU-R recommendation.

NeQuick FORTRAN 77 code was submitted to and accepted by the ITU-R in 2000 and revised in 2002. It is downloadable from the Internet [11], is referred to either as *version 1* or ITU-R and constitutes the current baseline for Galileo. This package, of which a comprehensive description of the implementation can be found in [12], includes also numerical integration subroutines allowing to compute $vTEC$ and $sTEC$.

Since then the model has undergone a series of evolutions leading to a **second version** [13, 14] available from the model designers[5].

- *Bottomside simplifications* and associated changes in the calculation of the E and F_1 peak amplitudes and f_oF_1 [15] allow to avoid some unrealistic features.
- Topside soundings data were processed to modify the formulation of the *shape parameter* k involved in the *topside* thickness parameter $B_{top}^{F_2}$ calculation [16]. It was previously computed on the basis of two formulas, one for months between April and September and the other for the rest of the year, which are replaced by a single one in NeQuick 2.
- Finally a *new modified dip latitude (MODIP) file* was introduced for MODIP interpolation in the framework of CCIR maps use [17].

Consequently potential improvements need to be assessed through different methods among which the ones described in next section.

2.2 Analysis Method

Among the different analysis methods using NeQuick in different ways, we chose as a first step to **uncouple NeQuick formulation from its underlying data** [18, 19]. To this extent, we replaced the CCIR maps of f_oF_2 and $M(3000)F_2$ by their measured values by means of an ionosonde, which we call ionosonde parameters from now on. In other words, we constrained the model to a daily behaviour, anchoring it in a real ionosphere, instead of considering the monthly median output.

In a second step, we implemented an **ingestion scheme** similar to the one which will be run at each Galileo Sensor Station [3, 4]. This technique consists in adapting NeQuick to measured TEC by means of an effective parameter [20], the effective ionisation level Az, playing the role of the solar flux in NeQuick input. For a given station and day, we computed the Az value which minimised the Mean Square (MS) sTEC difference

$$MS = \left\langle \left(sTEC_{mod}(Az) - sTEC_{meas}\right)^2 \right\rangle \tag{2}$$

using the Brent optimisation method [21] with all available satellite-to-receiver ray paths[6].

Given these uses of NeQuick, we compared its results using **two kinds of measurements**: $vTEC$, denoted only as TEC in the following, computed by GPS and vertical electron density profiles from an ionosonde. We took there advantage of collocated independent data, a part exploited to constrain the model and the other as reference.

We performed the assessment by means of a **home-made Matlab GUI** enabling us to browse measured and modelled TEC and electron density profiles as well as input data. We also included a module allowing to analyse statistically TEC differences computing mainly bias and standard deviation for each year, month, day and UT in a month or year (cf. table 1).

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[5] Pr Sandro Radicella and Bruno Nava from ICTP in Trieste (`http://arpl.ictp.trieste.it/`).

[6] To limit computation time, we actually used a 30' sampling rate.

In the following sections, we adopt **five different approaches**:

- we compare the global TEC behaviour of each version of the model with GPS TEC examining *yearly statistics*,
- we highlight the influence of the *modification of the topside shape parameter k* considering separately the periods corresponding to both formula in NeQuick 1,
- we show the critical importance of the topside *splitting TEC* between its bottomside and topside contributions,
- we confirm our observations examining *monthly statistics*
- and we show how residual errors are resorbed using *slant TEC ingestion*.

2.3 Data Sets

We gathered manually validated ionosonde parameters and electron density profiles obtained by **digisondes** [22] and **GPS TEC data calibrated by means of Global Ionospheric Maps (GIM)** [23]. The latter provide a reference global $vTEC$ used to level the geometry-free combination of carrier phases. Consequently potential problems related to code hardware delays, multipath and noise [24] are reduced as no pseudorange measurement is directly involved in TEC computation. To obtain $vTEC$, we selected $sTEC$ values corresponding to an elevation greater than 61.8°, we converted them to vertical using a mapping function associated to a 400-km thin shell height and we computed their mean over 15-minute periods (equivalent to subionospheric points within a radius of 200 km around the station; similar to [25]).

We fixed the framework of this study over a **high solar activity** period (year 2002) and **mid-latitudes** selecting three European locations with collocated digisonde and IGS/EUREF station (cf. fig. 2).

Finally we highlight the **interest of manual validation** of ionosonde parameters showing the 95% percentile of f_oF_2 differences between auto-scaled and manually validated values (cf. fig. 3). We also give the **availability** levels of each kind of data and for their combined use (cf. fig. 4). We count maximum 35040 GPS TEC values (one every quarter) and 8760 DGS parameters couples and profiles (soundings every hour). We explain partially the lower availabilities

- for El Arenosillo digisonde, by a lack of data between July 25th and October 25th,
- for Dourbes digisonde, because of January is missing
- and for TEC data, because of the odd-hour IONEX format for the GIM leads to a systematic gap between 23 and 1 UT.

Table 1. Statistical characterisation of differences in TEC analysis

$\text{Bias} = \langle TEC_{mod} - TEC_{meas} \rangle$	$\text{Standard deviation} = \sqrt{\langle (TEC_{mod} - TEC_{meas} - Bias)^2 \rangle}$
$\text{Relative parameter} = \frac{\text{Parameter}}{\langle TEC_{meas} \rangle}$	$\text{Evolution} = \frac{\text{Parameter}_{NeQuick\ 2} - \text{Parameter}_{NeQuick\ 1}}{\text{Parameter}_{NeQuick\ 1}}$

Fig. 2. Collocated digisondes and IGS/EUREF stations

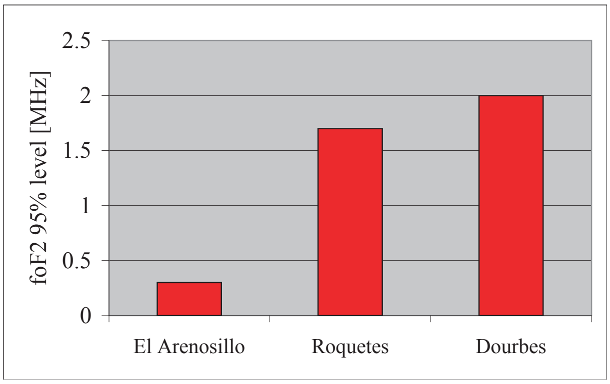

Fig. 3. Influence of ionosonde scaling validation on f_oF_2

3 ANALYSIS

3.1 Yearly Statistics

Examining yearly statistics allows us first to observe the **influence of latitude**: $vTEC$ mean decreases northwards (cf. fig. 5). We then state an average **underestimation** of both versions of the model even bigger (around 20%) for NeQuick 2. However a potential bias in TEC data has to be taken into account regarding the involvement of GIM. Indeed the latter show globally higher TEC values compared to other data sets which could be due to calibration methods among others. Considering the **lower (around 20%) standard deviation** for NeQuick 2, we tend to conclude to an improvement from the second version of the model.

3.2 Influence of k Unification

As described in section 2.1, the major modification between both NeQuick versions is related to the topside. The two formulas (one for April to September and the other for October to March) for the shape parameter k in NeQuick 1 were replaced by a single one in NeQuick 2. It reveals thus itself interesting to **compute statistics separately for each period corresponding to the two former formulas**.

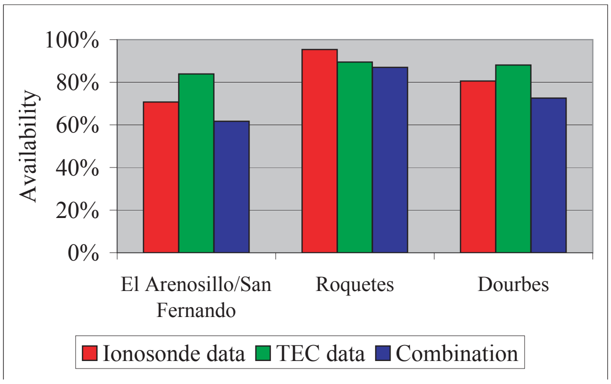

Fig. 4. Data availability

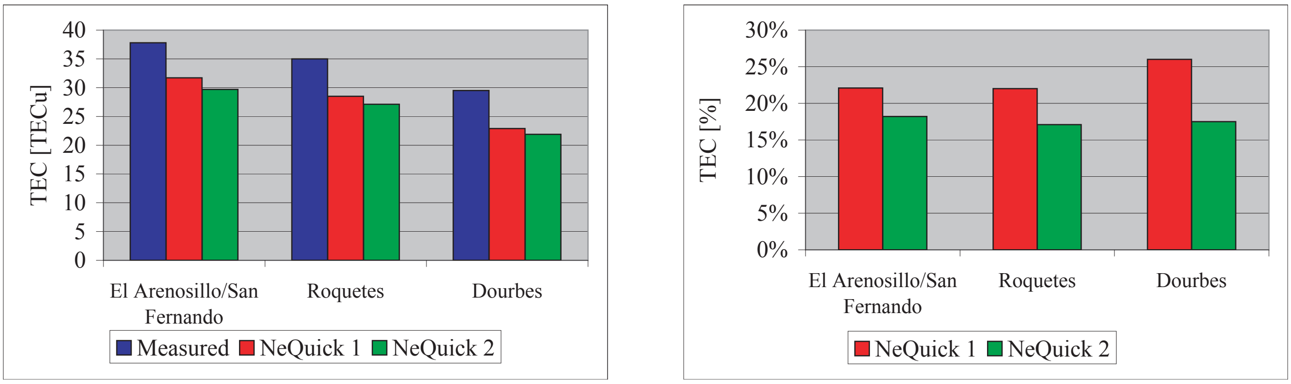

Fig. 5. Yearly TEC mean (left) and relative standard deviation (right)

We then observe different performances for each period especially regarding statistics evolution from one version to the other (cf. fig. 6). For April to September, we state a lower (20%) bias and slightly higher standard deviation in NeQuick 2. For October to March however, the bias, lower than for the first period in NeQuick 1, becomes much higher (200%)[7] and the standard deviation, higher between April and September for the first version of the model, decreases by about 15% in the second version. This **second period becomes hence more homogenous** with the first one and mostly influences the global statistics.

3.3 TEC Splitting

To feel even more confident about the impact of the modification in the topside formulation, we could advantageously **distinguish between bottomside and topside contributions to the TEC**. To this extent, we integrated the bottomside electron density profile from the digisondes to compute the bottomside TEC[8]. Then we subtracted this value to the GPS TEC to obtain an estimate of the topside TEC for which conclusions have to be drawn with caution as it includes the whole GPS TEC uncertainty.

This procedure enables us to highlight the **big proportion of TEC lying within the topside** (more than 75% on average, cf. fig. 7). We thus put into perspective the importance of the bottomside formulation – eventually slightly worse with NeQuick 2 – justifying the interest of the simplifications introduced in the second version of the model (cf. section 2.1). We also observe the **favourable evolution of the topside statistics** corresponding to the global values and driving them.

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[7] This high percentage is due to the low value of NeQuick 1 bias (around 2.5 TECu).

[8] We have not had access to profiles for Roquetes digisonde yet so that we did not apply TEC splitting to that station.

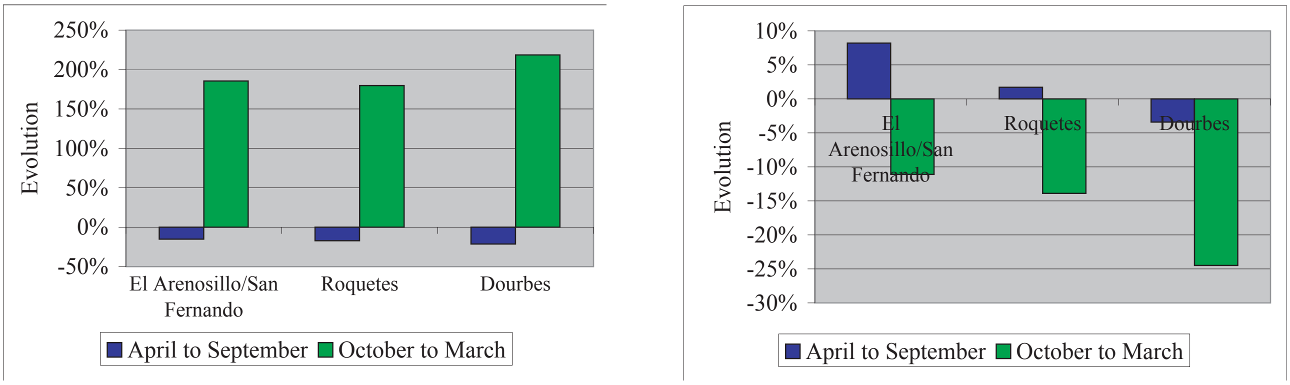

Fig. 6. Evolution of TEC bias (left) and standard deviation (right) between NeQuick versions

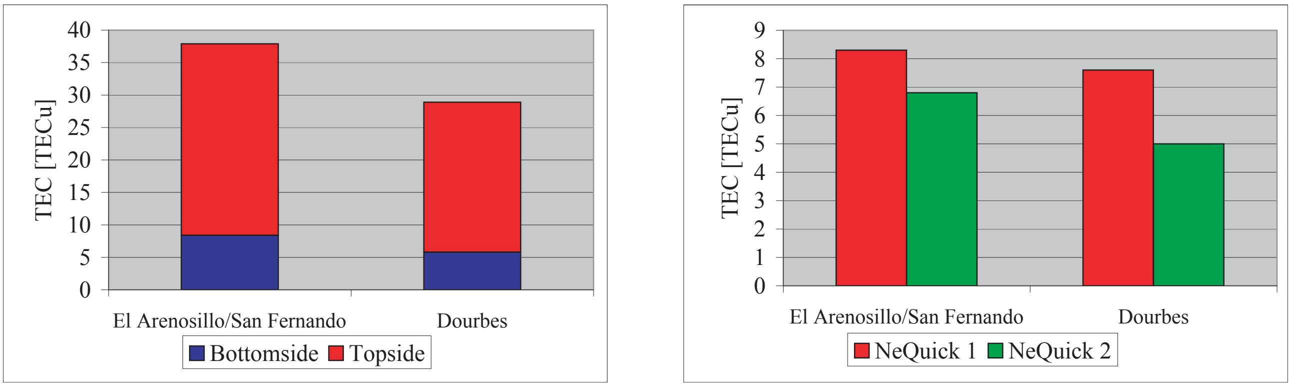

Fig. 7. Proportion of TEC within bottomside and topside (left) and yearly topside TEC standard deviation (right)

3.4 Monthly Statistics

Another interesting insight to handle NeQuick formulation and the consequences of its modification consists in examining monthly statistics. To this extent, we chose Roquetes for its higher data availability. Fig. 8 highlights the **double behaviour** described in section 3.2 **for NeQuick 1** and the **homogenisation** from the topside shape parameter k unification **in NeQuick 2**. We also note an improvement in bias and standard deviation for August and September (idem for Dourbes), two months missing in El Arenosillo data set (cf. section 2.3). If they had been present, they would apparently have influenced positively the various statistics presented in previous subsections.

3.5 Slant TEC Ingestion

Finally moving towards NeQuick use in satellite navigation, we examine **how slant TEC ingestion can absorbe the above described intrinsic residual errors**. To this extent we compute daily Az values for Dourbes station and corresponding vertical TEC using them as effective solar flux. By comparison with previous yearly statistics (cf. section 3.1), we obtain **lower bias (about three times) and standard deviation** (cf. fig. 9). Furthermore the conclusion about the improvement from NeQuick 2 becomes even clearer: both bias and standard deviation decrease by respectively 15% and 10%.

We also quantify the impact of using Az values of the day before according to the Galileo single frequency ionospheric correction algorithm: the standard deviation increases by about 35%.

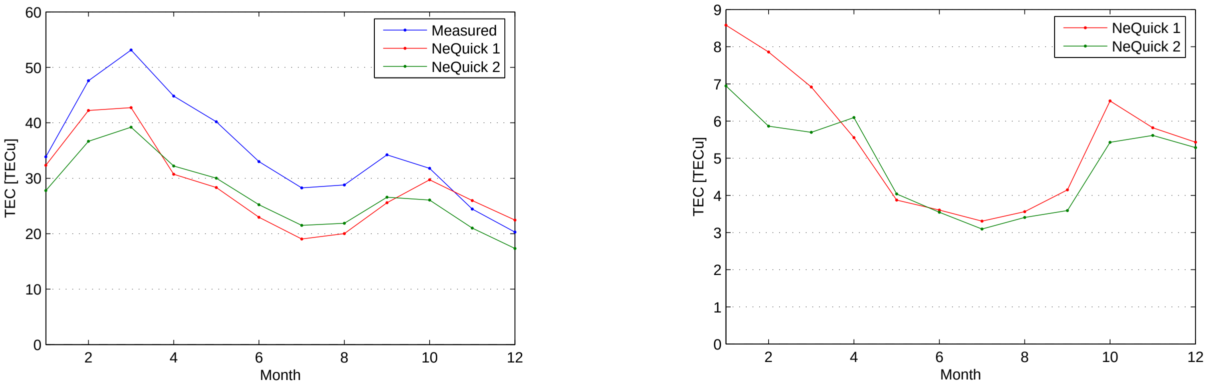

Fig. 8. Monthly TEC mean (left) and standard deviation (right) for Roquetes

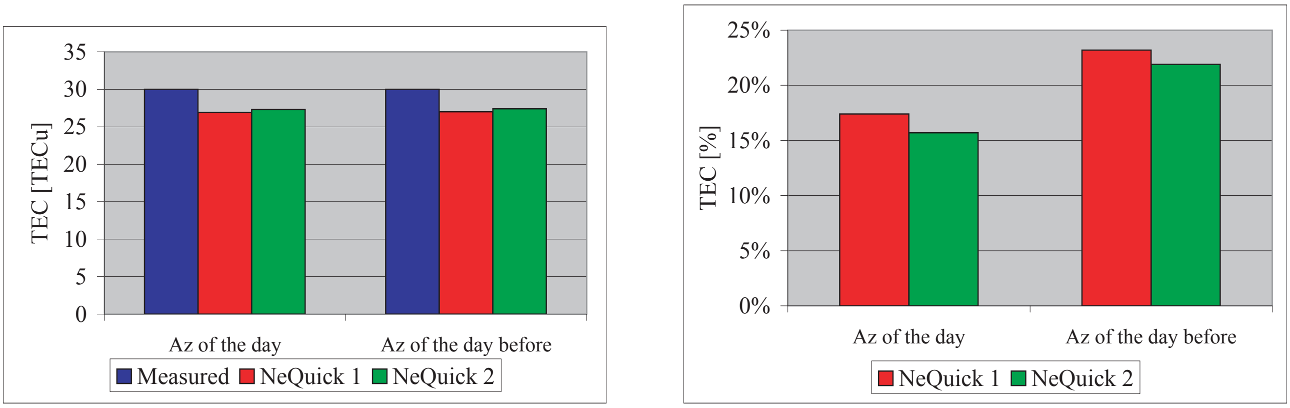

Fig. 9. Yearly TEC mean (left) and relative standard deviation (right) using Az obtained from slant TEC ingestion at Dourbes

4 CONCLUSION AND PERSPECTIVES

As a corner stone in the Galileo single frequency ionospheric correction algorithm (SF ICA), the **NeQuick model is improved** thanks to several studies. The present assessment lies within this scope insofar as it investigates the model and its latest developments for three mid-latitude stations collecting collocated ionosonde and GPS TEC data.

Conditioning NeQuick with ionosonde data, we first analysed statistically the difference between GPS-derived vertical TEC for Dourbes, Roquetes and El Arenosillo/San Fernando stations and corresponding modelled values for the last solar maximum in 2002. We found **standard deviations decreasing by 20% to reach less than 20% in relative values with NeQuick 2**; biases increasing by 20% up to 25% (care must be taken about GPS TEC data regarding the bias).

To explain this progress, we highlighted the influence of the **unification of the topside shape parameter** k as the two former formulas corresponded with periods exhibiting opposite behaviours. We also showed the **importance of the topside** accounting for 75% of the TEC on average and we confirmed all our observations examining **monthly statistics**.

In a second step, we examined preliminary results of **slant TEC ingestion**. Computing a daily effective ionisation level Az playing the role of the solar flux, we also obtained better statistics with NeQuick 2 (decrease of 15% in bias and 10% in standard deviation). Finally we quantified the relative deterioration using Az values of the day before according to the Galileo SF ICA.

The present study constitutes a basis of comparison for further investigation of more global uses of the model. We will indeed be able to observe how **data ingestion** techniques (not only sTEC) can further accommodate the remaining mismodelling as well as the adaptation of the CCIR maps to daily situations. Finally we will assess the **Galileo SF ICA** with potential suitable evolutions of NeQuick.

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