

Assessment of the NeQuick Model at Mid-latitudes using GPS TEC and Ionosonde Data

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ABSTRACT

The **ionosphere** plays a crucial role in Global Navigation Satellite Systems (GNSS) accuracy. In extreme cases, this electrically charged part of the atmosphere can lead to **errors in positioning** exceeding 100 *m*. At first approximation, ionospheric effects depend mainly on the total content in free electrons of the ionosphere ("total electron content", TEC). The modelling of the latter parameter reveals thus itself critical in particular for **single frequency receivers**, the most common ones constituting the mass market. In the framework of GALILEO, the **NeQuick model** has been chosen to this extent and will be integrated into a global algorithm providing the users with daily updated information.

In order to reach the specified correction level, the model itself and its latest evolutions as well as its use for GALILEO are **investigated**. As a first step in a thorough analysis, we take benefit of **ionosonde and GPS TEC data** from the Dourbes Geophysical Observatory (Belgium) to study the mid-latitudes. Constraining the model with ionosonde measurements, we first investigate the difference between GPS-derived vertical TEC (vTEC) for Dourbes station and corresponding values from NeQuick for the latest years (for solar maximum in 2002 and minimum in 2006). With this approach, we reach **residual errors of about 20% RMS for 2002 and 30% for 2006**. Through a **focusing process**, we identify then gradually best and worst months and days for which we observe the evolution between two versions of NeQuick. We highlight among others **improvements from the latest modification in the topside formulation** which appears clearly in the electron density profiles examined at the end of the assessment.

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 kilometers 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.

$$I_g = \frac{40.3}{f^2} \int_{sat.}^{rec.} N_e ds = \frac{40.3}{f^2} sTEC \quad (1)$$

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 in particular 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]. 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 NEQUICK MODEL

NeQuick belongs to the "DGR family" of ionospheric models known as "**profilers**" [4, 5]. 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. NeQuick is the simplest one and was adopted by the ITU-R recommendation for TEC modelling [6]. The NeQuick model is divided into two regions [7]: the *bottomside*, up to the F_2 -layer peak, consists of a sum of five semi-Epstein layers¹ [8] 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 layers², the thickness parameters B_{bot}^L and B_{top}^L 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 [9] for the F_2 characteristics³ 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.

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 [10], 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 [11], 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** [12, 13] available from the model designers⁴.

- *Bottomside simplifications* and associated changes in the calculation of the E and F_1 peak amplitudes and f_oF_1 [14] 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 [15].
- Finally a *new modified dip latitude (MODIP) file* was introduced for MODIP interpolation in the framework of CCIR maps use [16].

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

¹The prefix "semi" means that different thickness parameters are used below and above the layer peak.

² L stands for the layer index which possible values are E , F_1 and F_2 .

³Note 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.

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3 TOOLS AND 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**. To this extent, we replaced the CCIR maps of f_oF_2 and $M(3000)F_2$ by their measured values by means of a digisonde [17] which we call DGS 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. We decided not to feed NeQuick with digisonde data for f_oE and f_oF_1 because they are less available and sometimes resulting from a model [18]. We should also have needed to use NeQuick formulation for some of the missing values, especially for f_oF_1 , leading to a mix of measured and modelled data for these parameters.

Furthermore we needed solar activity indices as additional input that we find from online data centers (monthly average solar flux Φ for f_oE from the US National Geophysical Data Center (NGDC) in Boulder⁵ and monthly smoothed sunspot number R_{12} for topside parameter k from the Solar Influences Data analysis Center (SIDC) in Brussels⁶).

Given this use of NeQuick, we compared its results with **two kinds of measurements**: vertical TEC, the valuable parameter for navigation purpose, computed by GPS [19] and vertical electron density profiles from a digisonde. We took there benefit of collocated independent data, a part exploited to constrain the model and the other as reference. As NeQuick is not expected to represent correctly geomagnetically active periods leading sometimes to abnormally low or high TEC values, we removed these periods for the statistical analysis thanks to geomagnetic activity indices from online data centers (Kp from the GeoForschungsZentrum in Potsdam⁷ and Dst from World Data Center 2 in Kyoto⁸).

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 root mean square (RMS) for each year, month, day and UT in a month or year (cf. table 1).

In the following sections, we present the adopted **focusing process**: for a year of data,

- we compare the global TEC behaviour of each version of the model with GPS TEC,
- we turn to the best (resp. worst) month for which we select the best (resp. worst) day on relative RMS sense and we describe the daily TEC profile
- and we observe the electron density profiles associated to a small (resp. big) TEC bias in the neighbourhood of the daily maximum of measured TEC.

Figures will systematically depict the results for v1 on the left and for v2 on the right.

⁵<http://www.ngdc.noaa.gov/stp/SOLAR/FLUX/flux.html>

⁶<http://www.sidc.be/sunspot-data>

⁷http://www.gfz-potsdam.de/pb2/pb23/GeoMag/niemegk/kp_index/

⁸<http://swdcwww.kugi.kyoto-u.ac.jp/wdc/Sec3.html>

Table 1. Statistical characterization of differences in TEC analysis

	Absolute	Relative
Bias	$\langle TEC_{meas} - TEC_{mod} \rangle$	$\frac{\langle TEC_{meas} - TEC_{mod} \rangle}{\langle TEC_{meas} \rangle}$
RMS	$\sqrt{\langle (TEC_{meas} - TEC_{mod})^2 \rangle}$	$\frac{\sqrt{\langle (TEC_{meas} - TEC_{mod})^2 \rangle}}{\langle TEC_{meas} \rangle}$

Table 2. Maximum amounts of data and amounts of available data for 2002 and 2006

	Maximum	2002	%	2006	%
GPS	35040	33979	97.0	34567	98.7
+ DGS	8760	6973	79.6	6150	70.2
+ storm filter	8760	6076	69.4	6009	68.6

Table 3. Yearly average characteristics

	2002	2006
TEC_{meas} [TECu]	24.6	6.9
Number	6076	6009
R_{12}	100.8	16.2
Φ [$10^{-22} W m^{-2} Hz^{-1}$]	175.1	80.2
f_oF_2 [MHz]	7.4	4.5
$M(3000)F_2$	2.95	3.30

We applied this methodology using data from the **Dourbes Geophysical Centre**⁹ in Belgium (50.1°N ; 4.6°E) where are installed the GPS EUREF station "DOUR" and the UML digisonde DGS-256 "DB049". We collected data for *two years* characterized by different solar activity levels (high in 2002, low in 2006) for which we need to consider the *number of points* for a correct statistics interpretation (cf. table 2). For each year, we count maximum 35040 GPS TEC values (one every quarter) and 8760 DGS parameters couples and profiles (soundings every hour in 2002 and every 20 minutes in 2006 ; we kept the more restrictive one-hour rate). For the geomagnetic activity filter, we chose respectively 5 and $-50 nT$ for Kp and Dst thresholds (storm thresholds from [20]). Note that technical problems explain the rather low data availability for 2006.

4 TEC ANALYSIS

4.1 Yearly Behaviour

The analysis of global TEC behaviour on a yearly basis informs us about the impact of **solar activity** insofar as we selected extreme conditions i.e. high and low levels. Table 3 illustrates this choice as the average solar indices are lower in 2006 than in 2002 as well as measured TEC. This parameter we consider in this section follows to a certain extent the evolution of the denser region of the ionosphere, the F_2 peak. Indeed the latter electron concentration and height decrease respectively in function of f_oF_2 and of the inverse of $M(3000)F_2$.

Examining the yearly statistics for modelled TEC, we state an average low underestimation in 2002 which increases with v_2 (cf. table 4). Nevertheless this version seems better because of its **lower RMS** despite the bigger bias attesting really less spread differences. We note the same improvement in 2006 where the RMS decreases even more (almost a half against a third) and the big average overestimation becomes a really small underestimation. However we must moderate these observations for 2006 because of the lower availability and quality of auto-scaled data partially due to technical problems (cf. section 3) and the lower TEC values. These implies partly bigger relative statistics and a growing influence of measurement accuracies (e.g. 2-3 TECu for GPS TEC [21]).

⁹<http://www.meteo.be/CPG/Index.htm>

Table 4. Yearly statistics

	2002			2006		
	v_1	v_2	Evolution	v_1	v_2	Evolution
TEC_{mod} [TECu]	23.0	22.3	96.9%	8.7	6.6	76.3%
Bias [TECu]	1.6	2.3	143.9%	-1.8	0.2	-13.2%
Relative [%]	6.5	9.4		-26.5	3.5	
RMS [TECu]	7.7	5.2	67.3%	3.8	2.1	56.2%
Relative [%]	31.4	21.1		55.1	31.0	

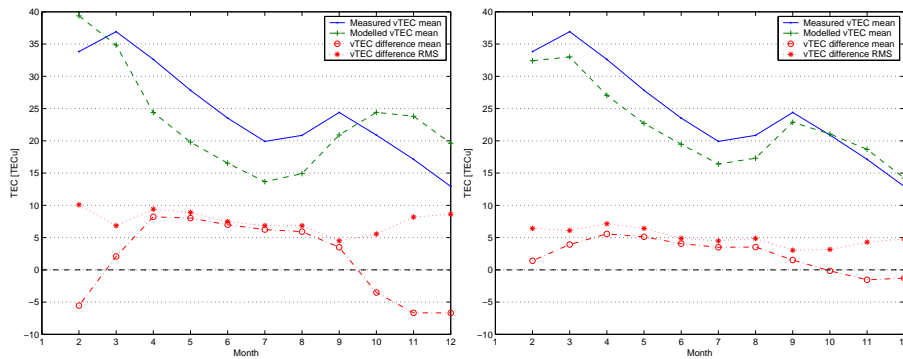


Fig. 1. Monthly TEC values for 2002 (v1 left and v2 right)

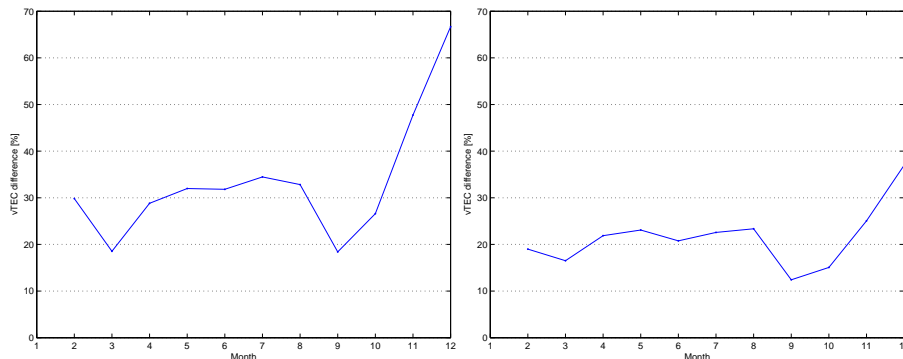


Fig. 2. Monthly TEC difference relative RMS for 2002 (v1 left and v2 right)

4.2 Monthly Behaviour

We get now to a finer timescale to inspect the **seasonal** variations and we take the year 2002 as an example considering the higher data availability (cf. section 3). The NeQuick representation of equinoxes maxima (cf. fig. 1) appears as the best among all months (cf. fig. 2). It even improves with v2 which ensures also a better correspondance eliminating February maximum. We consider thus *September* as the best month (lowest relative RMS) for both versions (18.4% and 12.4% RMS) for the following of the analysis.

We observe then a double behaviour for v1: an overestimation occurs during autumn and winter and an underestimation takes place in spring and summer. We attribute this phenomenon to the topside shape parameter k formulas [7] of which the selection corresponds to these periods. Moreover they are replaced by a unique formulation in v2 [15] leading to the disappearing of the observed difference even if November and December still show a different behaviour than the other months (average overestimation). We further note a minimum in measured TEC around winter solstice which implies high relative RMS for *December* (66.7% and 37.0%). Consequently we choose this month as worst allowing to study the suitable evolution of the above-mentioned behaviour between both NeQuick versions. Indeed most of its exaggerated values appropriately decrease accounting for the bigger average underestimation in v2 (cf. subsection 4.1).

We can now refine the conclusions of subsection 4.1 insofar as modelled TEC decreases on average with v2 essentially in autumn and winter but not enough for autumn. In spring and summer, it increases towards measured values in high solar activity period but decreases a little below reference data for low solar activity level. This evolution corresponds to the **unification of the topside shape parameter k** which **enhances NeQuick seasonal performances** as indicated by all decreasing relative RMS statistics.

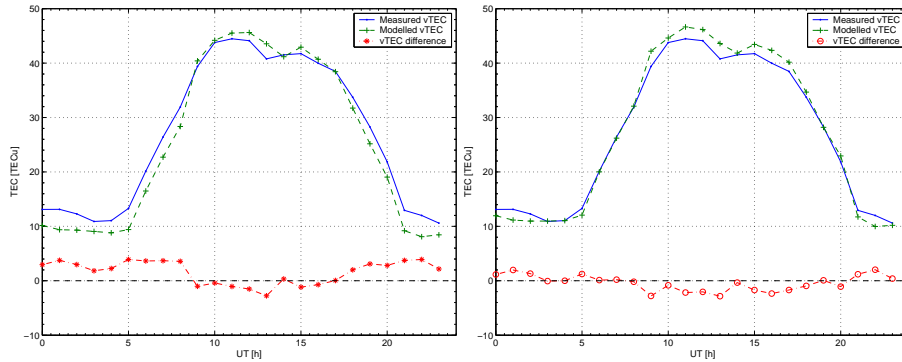


Fig. 3. Hourly TEC values for September 22nd, 2002 (v1 left and v2 right)

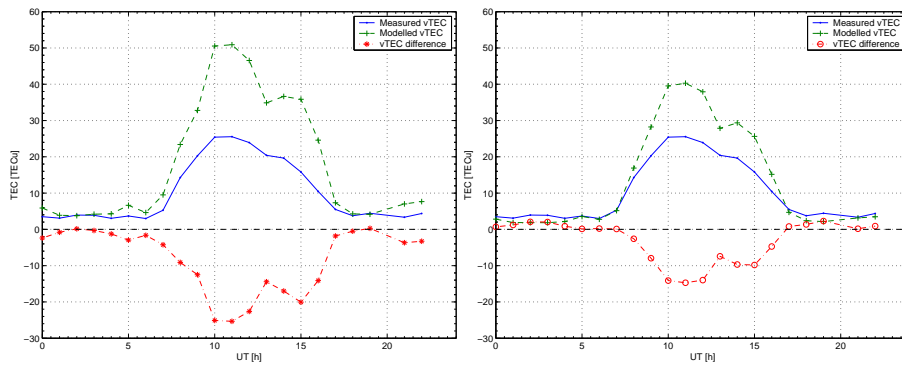


Fig. 4. Hourly TEC values for December 29th, 2002 (v1 left and v2 right)

4.3 Daily TEC profiles

For each month identified in previous section, we select similarly the best and worst days on relative RMS sense, corresponding to September 22nd and December 29th, and we study the daily TEC profile.

Fig. 3 shows the daily TEC profile for September 22nd with a maximum (45 TECu) just before local noon and a minimum (10 TECu) in the end of the night depicting the **daily TEC behaviour** (maximum the end of a period of increasing ionization and minimum just before the sun action reappears). The evolution between both versions of NeQuick, an average underestimation becoming a little overestimation, looks like a constant offset for all hours but smaller for some of them (10, 12, 13, 14 and 15) which already own the lower differences. These become then comparable with GPS TEC uncertainty ($2 - 3 \text{ TECu}$) for all hours attesting the effectiveness of NeQuick for this situation. To deepen the analysis, we will examine the electron density profiles associated with the smaller TEC bias in the maximum around local noon, at $10 \text{ Universal Time (UT)}$ for both versions.

For a high solar activity level, TEC around solstice winter reveals itself far inferior to autumn (cf. fig. 4) with daily maximum of 26 TECu and minimum of 3 TECu which also follows later sunrise. The overestimation, decreasing more like a scaling with little lower low TEC (-2 TECu) and high values appreciably eroded (-10 TECu), remains huge with a maximum at 11 UT for which we will study the electron density profiles.

5 ELECTRON DENSITY PROFILES ANALYSIS

5.1 Best Month in High Solar Activity

Even if TEC receives our principal interest because of its importance for navigation, the main advantage of NeQuick by comparison with other models such as Klobuchar algorithm resides in its ability to predict electron densities integrated in a second step. It permits us now to pursue our investigation decomposing TEC in its

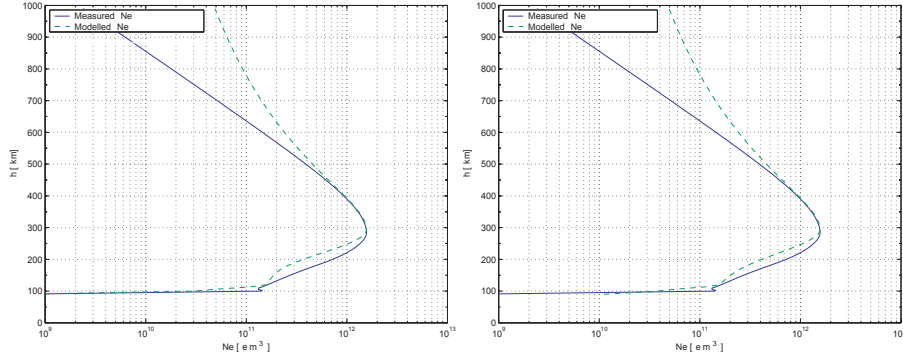


Fig. 5. Measured and modelled profiles for September 22nd, 2002 at 10 UT (v1 left and v2 right)

Table 5. Profiles characteristics for September 22nd, 2002 at 10 UT (v1 left and v2 right)

	Reference	v1	v2
TEC [TECu]	43.8	44.2	44.6
TEC_{bot} [TECu]	13.6	11.4	11.7
TEC_{top} [TECu]	30.2	32.8	32.9
B_{bot}^{eq} [km]	43.3	36.2	37.4
$B_{bot}^{F_2}$ [km]		32.3	
$B_{top}^{F_2}$ [km]		58.1	58.4
Ratio		1.80	1.81

underlying vertical electron density profile. However we will miss a potential part of the difference between measured and modelled TEC as errors on DGS parameters will affect both measured and modelled profiles in a similar way.

Regarding the bottomside on the one hand, the region we may compare with ionosonde profiles as the topside of the latter is modelled [22], we state an underestimation of the electron density which evolves well towards a denser profile in v2 thanks to the developments in the E and F_1 layers. On the other hand, we cannot distinguish any clear evolution of the topside representation between NeQuick versions so that we need to try somehow to dissociate it from the bottomside. To this extent, we integrate numerically the bottomside profiles and we subtract the obtained bottomside TEC (TEC_{bot}) from corresponding global TEC to get an estimate of topside TEC (TEC_{top}).

For September 22nd at 10 UT, all TEC values slightly increase with v2 compared to v1 (cf. table 5) which was expected for both bottomside and global profiles. In the case of the topside, it corresponds to the modification of the shape parameter k leading to a higher thickness parameter $B_{top}^{F_2}$. Anyway we state that NeQuick still overestimates the topside highlighting for the first time a compromise between topside and bottomside. The apparent very good behaviour in TEC appears in fact as a compensation from the too dense topside to the too weak bottomside.

We would thus like to quantify the bottomside thickness to evaluate $B_{bot}^{F_2}$ accuracy which constitutes a potential source of error we did not consider yet. Computing so-called equivalent thicknesses B_{bot}^{eq} dividing TEC_{bot} by $2 N_m F_2$ could constitute an interesting means and confirms the improvement of v2, to be extended. More rigorously, we should follow $B_{bot}^{F_2}$ definition [4] calculating the height or gradient of the inflection point at the base of the F_2 layer to compare pseudo-thicknesses but we would then need a better height resolution than 10 km. In this case, a raise of $B_{bot}^{F_2}$ seems suitable.

5.2 Worst Month in High Solar Activity

Between the E and F_2 peaks, the latest version of NeQuick computes little higher electron concentrations (cf. fig. 6) as for the best case and for the same reason (E and F_1 layers modifications). However NeQuick inflates

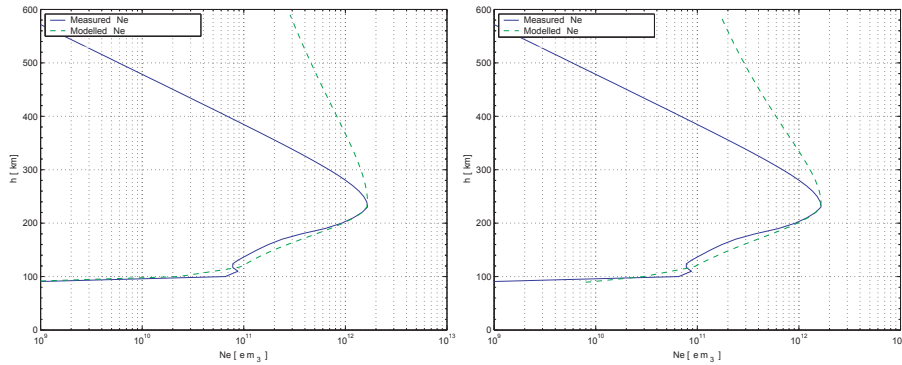


Fig. 6. Measured and modelled profiles for December 29th, 2002 at 11 UT (v1 left and v2 right)

Table 6. Profiles characteristics for December 29th, 2002 at 11 UT

	Reference	v1	v2
TEC [$TECu$]	25.6	50.9	40.3
TEC_{bot} [$TECu$]	6.7	8.1	8.2
TEC_{top} [$TECu$]	18.9	42.8	32.0
B_{bot}^{eq} [km]	20.2	24.5	24.9
$B_{bot}^{F_2}$ [km]		23.4	
$B_{top}^{F_2}$ [km]		71.9	53.8
Ratio		3.07	2.30

here this region accounting for a part of the global TEC overestimation. The latter drops between both versions following the topside as we can observe from the figure. The TEC dissociation corroborates our considerations of too dense bottom and topsides as well as the significant improvement from v2 new k formulation (cf. table 6). Nevertheless we still need to diminish TEC_{top} , which proves as the biggest component of TEC (almost three quarters in this case) by 13 $TECu$.

6 CONCLUSION AND PERSPECTIVES

6.1 NeQuick Evolution

As a corner stone in the GALILEO single frequency ionospheric correction algorithm, the **NeQuick model evolves** thanks to several studies. The present assessment lies within this scope insofar as it investigates the model and its latest developments for a mid-latitude station collecting collocated ionosonde and GPS TEC data.

Conditioning NeQuick with ionosonde data, we first analyzed statistically the difference between GPS-derived vertical TEC for Dourbes station and corresponding modelled values for the latest years (for solar maximum in 2002 and minimum in 2006). We found **relative RMS values of 21% in 2002 and 31% in 2006** for the latest version of NeQuick associated respectively to **improvements of 36.4% and 43.8%** of the results for the official GALILEO baseline available on line. We attribute this progress to the **unification of the topside shape parameter k** as the two former formulas corresponded with periods exhibiting opposite behaviours.

To deepen our understanding and confirm our assertions, we studied in detail two representative situations (best and worst days for high solar activity) for which we examined the daily TEC graphs and electron density profiles for an hour near the measured TEC maximum around local noon.

- We verified the consequences of the modification in the **topside** description, improving drastically the worst case, and we noticed **remaining problems** in this region including the greatest part of the electron content thanks to a TEC dissociation process.
- The latter showed us indeed the apparent **compensation between bottom and topsides** sometimes

hiding behind a global good adequation. Further progress in the topside could then come from changes in the bottomside as the thickness parameter of the first depends on the one of the second among others.

- Finally we watched **evolving differences** in the **bottomside** from developments in the E and F_1 layers so that we wondered about potential modifications in the F_2 **bottomside thickness parameter**, unchanged between NeQuick versions.

6.2 Future Work

Even if these results appear already very promising, we would feel even more confident about them by getting more acquainted with the **data**. We should check and improve their quality and availability if possible, in particular for the ionosonde in 2006, and investigate other filtering methods than with the only geomagnetic indices. On the one hand, a systematization of the **TEC dissociation process** and a **parameters analysis** could then provide us with some ideas of concrete evolutions to implement. On the other hand, a generalization to **other stations**, first at mid-latitudes then for all regions, would allow us to discuss the geographical representation of TEC.

Going back to a more global use of the model, we could afterwards analyse the performances **with the CCIR maps** and associated data ingestion and finally assess the **GALILEO single frequency ionospheric correction algorithm** with potential suitable evolutions of NeQuick.

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