IONOSPHERE MODELLING BASED ON THE NEQUICK MODEL AND GNSS DATA INGESTION

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ABSTRACT

As for other GNSS, the **ionospheric effect** remains one of the main factors **limiting Galileo accuracy**. For **single frequency users**, this contribution to the error budget will be **mitigated** by a global algorithm based on the **NeQuick** model. This quick-run empirical model provides flexible solutions for combining ionospheric information obtained from various systems, from GNSS to ionosondes and topside sounders thanks to which NeQuick has been designed. Hence it constitutes an interesting simulation tool not only serving Galileo needs for mitigation of the ionospheric effect but also widening the use of new data available thanks to the future European system.

In this study, we perform **slant TEC ingestion** - the optimisation procedure underlying the Galileo Single Frequency Ionospheric Correction Algorithm - into NeQuick for a **dozen of locations around the world** where both an ionosonde and a GPS receiver are installed. These collocated instruments allow us to compare measured and modelled vertical TEC in different ways showing for example global statistics or dependence towards latitude. We analyze such results for the year 2002 (high solar activity level) giving an interesting insight in the situation we could observe when Galileo reach its Full Operation Capability, during the **next solar maximum**[1].

Key words: ionosphere; mitigation; single frequency; Total Electron Content (TEC); NeQuick; ingestion.

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 from eq. 1 at first approximation.

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

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 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 *fall-back 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]. This algorithm relies on an optimisation procedure called ingestion for which it is interesting to understand how it can cope with NeQuick intrinsic weaknesses.

[1]Find material about this paper on http://orbi.ulg.ac.be/handle/2268/19132.

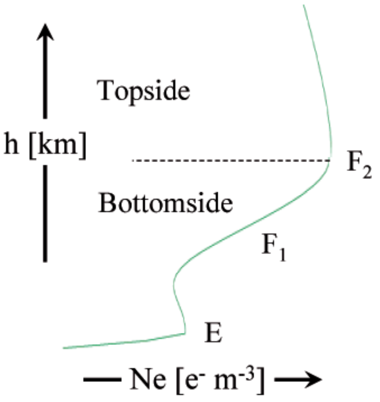

Figure 1. Electron density profile and characteristic regions

2. TOOLS AND METHOD

2.1. NeQuick Model

NeQuick belongs to the "DGR family" of ionospheric models known as "**profilers**". 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. The NeQuick model is divided into two regions [5]: the *bottomside*, up to the F_2-layer peak, consists of a sum of five semi-Epstein layers and the *topside* is described by means of an only sixth semi-Epstein layer with a height-dependent thickness parameter. The parameters of the Epstein layers are computed on the basis of the *ionosonde parameters*, f_oE, f_oF_1, f_oF_2 and $M(3000)F_2$. To obtain these critical frequencies and transmission factor, models can be used such as the CCIR maps [6] for the F_2 characteristics. A monthly median situation is then represented. However the power of NeQuick consists in its ability to accommodate other sources of data for these parameters e.g. measured values [11].

On the basis of position, time and solar activity index (solar flux or sunspot number) provided as input, the model returns the corresponding electron density. Its FORTRAN 77 code is downloadable from the Internet [7], 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 [8], includes also numerical integration subroutines allowing to compute $vTEC$ and $sTEC$.

In the recent years, a **second version** of NeQuick has been designed [9] and is available from the model designers[2]. The *main evolution* concerns the *topside* representation. Topside soundings data were indeed processed to modify the formulation of the *shape parameter* k involved in the topside thickness parameter calculation [10]. 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.

2.2. Data Ingestion

Ionospheric models such as NeQuick often use **solar activity indices as standard input**. These indices are based on solar observation and do not necessarily account perfectly for the solar activity in EUV radiations inducing the ionisation in the Earth atmosphere. Hence different **"effective"** indices have been developed from the combination of ionospheric models and experimental data. They allow to *drive a model towards measured values* by adapting it to a specific data set, a reconstruction technique usually referred to as data ingestion.

NeQuick has often been used in this framework in combination **with TEC data** [13, 12]. At a given time and for a given ray path, the TEC value obtained from the integration of NeQuick electron density profile depends monotonously on its solar flux input. The latter is then usually called *effective ionization level* Az and is computed by *minimising* the mismodelling between the model and a subset of TEC values. At vertical and for a chosen time, this corresponds simply to the difference between modelled and measured $vTEC$. For $sTEC$, the mismodelling is defined as the *Root Mean Square (RMS) difference*

$$RMS = \sqrt{\left\langle \left(sTEC_{mod}(Az) - sTEC_{meas}\right)^2 \right\rangle} \quad (2)$$

where <> denotes averaging. For a given station, Az can then be inferred epoch by epoch. In the context of the Galileo Single Frequency Ionospheric Correction Algorithm, daily Az values will be computed using $sTEC$ data for entire days [3, 4].

2.3. Data Sets

In this study, we use three kinds of ionospheric data: ionosonde parameters, $sTEC$ and $vTEC$. For the first, we consider manually validated measurements mainly obtained by **ionosondes**[3] and, for the others, **GPS-derived data calibrated by means of Global Ionospheric Maps (GIM)**[4]. The latter provide a reference global $vTEC$ used to level the geometry-free combination of carrier phases which contains $sTEC$ information [16]. Consequently potential problems related to code hardware delays, multipath and noise [17] are reduced as no pseudorange measurement is directly involved in

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

[3] Most of these measurements were downloaded from the World Data Center for Solar-Terrestrial Physics at Chilton, UK (http://www.ukssdc.ac.uk/wdcc1/data_menu.html).

[4] The data set used was computed at ESA using UPC GIMs.

TEC computation. To obtain $vTEC$, we select $sTEC$ values corresponding to an elevation greater than 61.8°, we convert them to vertical using a mapping function associated to a 400-km thin shell height and we compute their mean over 15-minute periods (equivalent to subionospheric points within a radius of 200 km around the station; similar to [18]).

For the sake of consistency and to enable the comparison described in next subsection, we select twelve locations with collocated ionosonde (DGS when digisonde [15]) and GPS station (cf. fig. 2 and tab. 1). We also focus on a **high solar activity** period (year 2002).

We give the **availability** levels of each kind of data and for the combined use of ionosonde parameters and $vTEC$ in fig. 3. We count maximum 1051200 GPS $sTEC$ values (two every minute corresponding to RINEX sampling rate), 35040 GPS $vTEC$ values (one every quarter) and 8760 sets of ionosonde parameters (soundings every hour). We explain partially the lower availabilities

- for ionosonde parameters, because no data is available for some months (Tromso: January to April; El Arenosillo: August and September; Townsville and Hobart: November and December; Dourbes and Boulder: January; Point Arguello: July)
- and for $vTEC$, because of the odd-hour IONEX format for the GIM leads to a systematic gap between 23 and 1 UT and because less $sTEC$ data are available at high elevation for high-latitude stations (Tromso and Sodankyla).

2.4. Analysis Method

The first step of our analysis consists in **uncoupling NeQuick formulation from its underlying data**. To this extent, we replace 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 constrain the model to a daily behaviour, anchoring it in a real ionosphere, instead of considering the monthly median output.

Our following and main focus involves an **ingestion scheme** similar to the one which will be run at each Galileo Sensor Station. We generate daily Az values using the Brent optimisation method [14] with all available satellite-to-receiver ray paths[5]. This allows us to observe how data ingestion can cope with NeQuick intrinsic residual errors.

To compare the results of these different uses of NeQuick, we consider **different statistics of** $vTEC$ (mean, standard deviation of the difference between measured and modelled values $\sigma_{\Delta TEC}$ or relative standard deviation $\sigma_{\Delta TEC,Relative}$; cf. eqs. 3 to 5) and different time frames (yearly or monthly).

$$\overline{\Delta TEC} = \langle TEC_{meas} - TEC_{mod} \rangle \quad (3)$$

$$\sigma_{\Delta TEC} = \sqrt{\left\langle \left(TEC_{meas} - TEC_{mod} - \overline{\Delta TEC}\right)^2 \right\rangle} \quad (4)$$

$$\sigma_{\Delta TEC,Relative} = \frac{\sigma_{\Delta TEC}}{\langle TEC_{meas} \rangle} \quad (5)$$

For computing yearly statistics, we also group the stations in **four regions** (cf. fig. 2) as long as the features of the ionosphere can be considered homogeneous within these regions. Finally we show the latitudinal behaviour of Az through its yearly mean at a subset of stations.

3. ANALYSIS

3.1. Ionosonde Parameters Constrain

Constraining NeQuick with ionosonde parameters allows us to investigate the intrinsic behaviour of the model. The ingestion scheme will indeed drive this initial situation towards measured TEC. In this context, we first investigate **yearly statistics of** $vTEC$. To obtain consistent statistics, we do not consider the months January to April for Sodankyla as ionosonde parameters are not available for Tromso in this period. The same statement applies to the Australian stations for November and December.

Fig. 4 shows us the *influence of latitude*: lower mean TEC values are observed at high-latitudes. We also state an average *underestimation* of about 25% of both versions of the model, which evolves differently between NeQuick 1 and NeQuick 2 for the different regions. It is increasing for mid-latitude Europe (by about 19%) and North America (by about 7%) and apparently decreasing for high-latitude Europe (by about 4%) and Australia (by about 15%). However we must not forget that several months of data are not included in the statistics for the last two regions. Hence further discussion on monthly statistics here under will help us to clarify the situation.

The observed underestimation has to be interpreted with caution. Indeed previous studies comparing different GPS TEC reconstruction techniques show that biases of several $TECu$ can appear between them [3, 4, 19]. These biases are related to the levelling techniques used by the different authors to compute phase ambiguities. Therefore the interpretation of the detected biases of the model is difficult.

The bottom panel of fig. 4 presents the *relative standard deviation* which amounts about 24%. Its reduction by about 17% for NeQuick 2 indicates us an *improvement from the second version of the model*. It is indeed decreasing by about 28% for Europe, about 13% for North

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

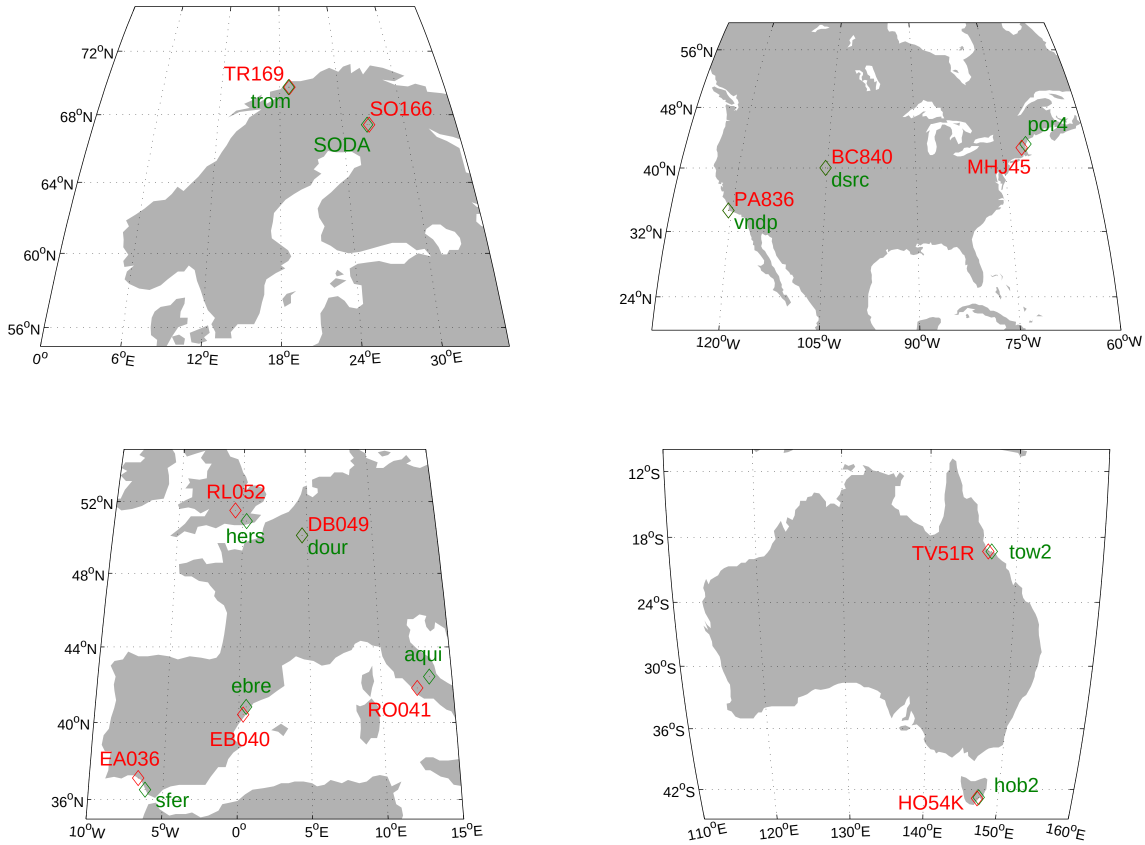

Figure 2. Collocated ionosondes and GPS stations (top left: high-latitude Europe; bottom left: mid-latitude Europe; top right; North America; bottom right: Australia)

America and very little for Australia keeping in mind the same reserve about missing data for this region.

To refine our analysis, we examine **monthly statistics** an example of which is given in fig. 5 for Millstone Hill. We find the same underestimation than before apart from November and December for NeQuick 1. Regarding the evolution from one version of the model to the other, we note decreasing biases for April to September, increasing underestimation for the rest of the year and decreasing standard deviations for the whole year apart from January. However the improvement suggested by the lower standard deviations appears rather small for the months April to September. The latter *6-month period* seems then *distinct from the other in terms of bias as well as standard deviation*.

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. Hence the two identified periods correspond to the k formulas in NeQuick 1, which enables to get different statistics for both of them. In the illustrated example, the bias decreases for the first period and the standard deviation for the second, leading to an *homogenisation from NeQuick 2*. An expected significative bias increase from November to March would then have influenced yearly statistics for high-latitude Europe and Australia in a consistent way with the other regions. A similar reasoning can be followed for November and December in the Australian region regarding the standard deviation.

Finally considering the overall scheme for this use of the model, we conclude that it provides the best results in mid-latitude Europe and that it works the worst in high-latitude Europe.

3.2. Slant TEC Ingestion

For this second part of the study, we do not need ionosonde parameters anymore. Hence the **yearly statistics** in which we are interested are not affected by missing months anymore. To perform $sTEC$ ingestion, we compute daily Az values which minimise the RMS difference between modelled and measured $sTEC$ data of each entire day at a given station. Then we run the model with these values to compute $vTEC$ to be compared with GPS $vTEC$.

Table 1. Stations identification

Location	Ionosonde	Type	Latitude [°N]	Longitude [°E]	GPS station	Network	Distance [km]
Tromso	TR169	DGS	69.6	19.2	trom	IGS	16
Sodankyla	SO166		67.4	26.6	soda	EUREF	9
Chilton	RL052	DGS	51.5	-0.6	hers	IGS	91
Dourbes	DB049	DGS	50.1	4.6	dour	EUREF	0
Rome	RO041		41.9	12.5	aqui	EUREF	93
Roquetes	EB040	DGS	40.8	0.5	ebre	IGS	0
El Arenosillo	EA036	DGS	37.1	-6.7	sfer	IGS	80
Millstone Hill	MHJ45	DGS	42.6	-71.5	por4	CORS	86
Boulder	BC840	DGS	40.0	-105.3	dsrc	CORS	0
Point Arguello	PA836	DGS	34.8	-120.5	vndp	IGS	24
Townsville	TV51R		-19.6	146.9	tow2	IGS	40
Hobart	HO54K		-42.9	147.3	hob2	IGS	14

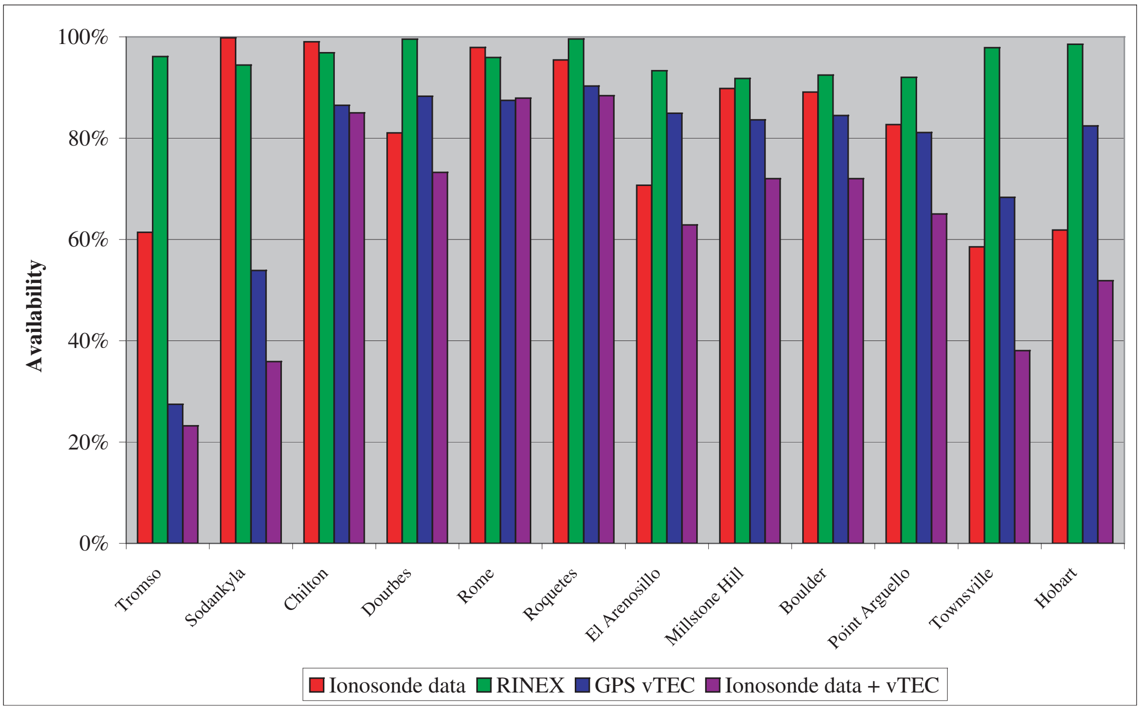

Figure 3. Data availability

We still observe an *underestimation* for both versions of NeQuick (cf. fig. 6) but it drops to about 8% by comparison with the use in combination with ionosonde parameters. Unlike previously, it is decreasing between NeQuick 1 and NeQuick 2 for mid-latitude Europe (about 22%), North America (about 14%) and even for Australia (about 48%) and slightly increasing for high-latitude Europe. Thus the bias is absorbed thanks to ingestion even better with NeQuick 2.

In terms of *relative standard deviation*, the average is *much smaller* than in the first part of the analysis (about 16%). The modifications of the second version of the model reduce the standard deviation by about 15%. Consequently both indicators show *better performances for NeQuick 2* and how $sTEC$ data ingestion can handle the model residual errors. They also confirm the best case for mid-latitude Europe and the worst for high-latitude Europe.

A final interesting characterisation of $sTEC$ ingestion results concerns the **effective ionisation level** Az. This parameter plays the role of the solar activity input of the NeQuick model. The use of the monthly smoothed sunspot number R_{12}, the adequate index to accommodate CCIR maps and provide monthly median output, or various solar flux averages leads to biases. In our case, the absorption of the corresponding underestimation obtained when constraining NeQuick with ionosonde parameters induces Az values (cf. fig. 7) *larger than the converted* R_{12} (yearly mean $\simeq 147[10^{-22}Wm^{-2}Hz^{-1}]$) *or even than solar flux* (yearly mean of daily flux $\simeq 179.5[10^{-22}Wm^{-2}Hz^{-1}]$). Even if the bias is larger *for NeQuick 2, lower values* of Az are computed thanks to its better performances. The dependence of Az towards latitude - *increasing towards high-latitudes* - justifies also

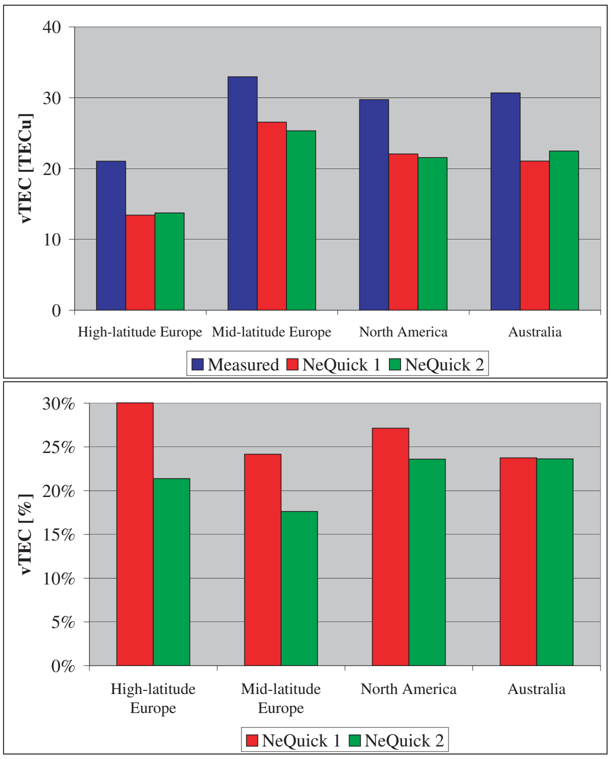

Figure 4. Yearly vTEC mean (top) and relative standard deviation (bottom) corresponding to DGS constrain

the representation of the global daily Az for the Galileo algorithm as a second order polynomial of the modip, a coordinate based on latitude and geomagnetic inclination [4].

4. CONCLUSION AND PERSPECTIVES

As a tool allowing to exploit different ionospheric data, the **NeQuick model** can be **used in combination with GNSS** $sTEC$ **data** in the framework of an **optimisation procedure called ingestion**. Instead of using solar flux as input, a new parameter, the "effective ionisation level" Az, is then computed in order to minimise the model mismodelling from a specific set of $sTEC$ data. This technique constitutes the basis of Galileo Single Frequency Ionospheric Correction Algorithm (SF ICA).

In order to understand how data ingestion accommodates the model residual errors, we **first constrained NeQuick with ionosonde data to characterise its intrinsic mismodelling**. We analysed statistically the difference between GPS-derived vertical TEC and corresponding modelled values for a dozen of stations distributed in four mid-latitude and high-latitude regions for the last solar maximum in 2002. We also considered the latest version of the model in order to quantify the evolution from the current ITU baseline. We found **standard deviations decreasing by about 17% to reach about 22% in relative values with NeQuick 2**; biases increasing by about 9% up to about 26% on average (care must be taken about GPS TEC data regarding the bias). Examining monthly statistics, 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 identified the region exhibiting the **best results as mid-latitude Europe** and the one with the **worst as high-latitude Europe**.

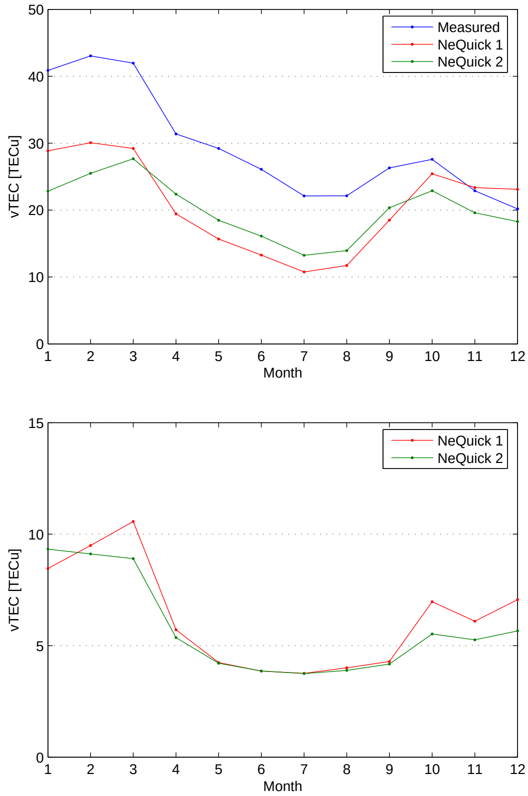

Figure 5. Monthly TEC mean (top) and standard deviation (bottom) for Millstone Hill

In a second step, we examined results of **slant TEC ingestion**. Computing daily Az values, we reached **biases of about 8% and standard deviations of about 16%**. We also obtained better statistics with NeQuick 2 (decrease of 22% in bias and 15% in standard deviation). Finaly we stated that Az values are much larger than the usual solar indices as they must drive TEC to accomodate residual errors. We also noted the **dependence of** Az **on latitude**: increasing towards high-latitudes.

To deepen our analysis, we will investigate statistics of **other ionospheric parameters** such as maximum electron concentrations. We will also perform a similar analysis with the **Galileo SF ICA** including potential suitable evolutions of NeQuick.

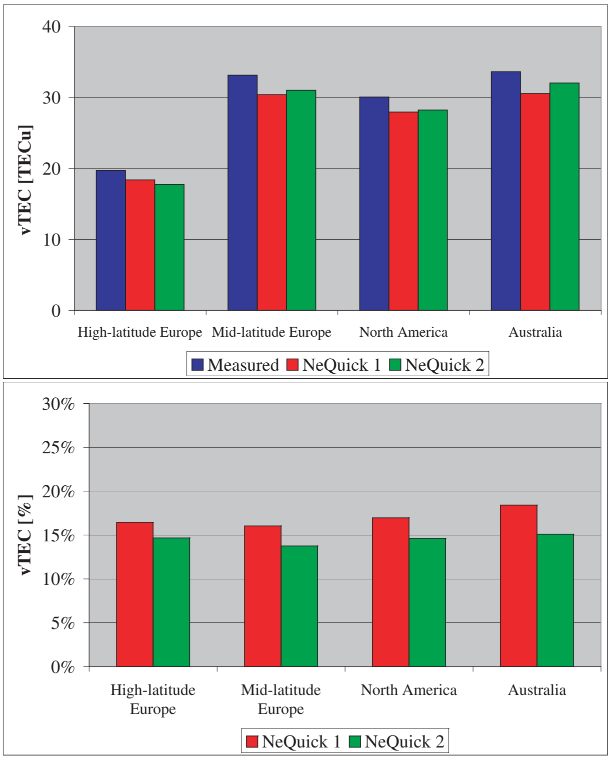

Figure 6. Yearly vTEC mean (top) and relative standard deviation (bottom) corresponding to slant TEC ingestion

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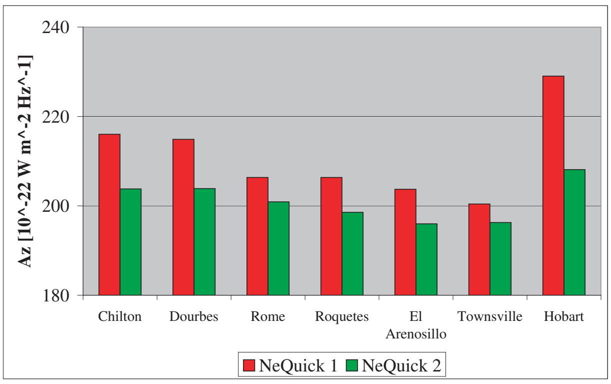

Figure 7. Yearly Az mean

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