Preliminary NeQuick assessment for future single frequency users of GALILEO

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Summary: The NeQuick model is the ionospheric model that will be used by the GALILEO single frequency user to compute ionospheric corrections. In this framework, the aim of this study is to show a preliminary assessment of the performance of the NeQuick model using as metrics an independent source of TEC (Total Electron Content) such as altimetric satellites (in this case, TOPEX/Poseidon) that provide direct measurements of TEC.

1. Introduction

GALILEO satellite system will provide a highly accurate, guaranteed global positioning service under civilian control besides being inter-operable with the pre-existing GPS and GLONASS systems. GALILEO signals will be affected by the atmosphere of the Earth. For a single frequency receiver, the main source of error is due to the portion over 60 km above the surface of the Earth that is the ionosphere. In this region, the carriers and codes experiment advances and delays (respectively) for the pseudorange values. Thus, as a first approximation, these effects could be considered to be produced by the free electrons of the ionosphere [5] and more than 99% of this advance/delay can be explained by a term inversely proportional to the squared frequency of the signal. This first approximation allows the correction of this term by using simultaneous measurements in both fequencies (f1=1574 MHz and f2=1227 MHz) computing the ionosphere free combination L_C for precise positioning. But for a GNSS single-frequency receiver, the Slant TEC (STEC) correction must be provided to users. In this context, there are several models that can be used to take into account this ionospheric term. The chosen model to generate the ionospheric correction coefficients for the GALILEO navigation message is the NeQuick model. It will be necessary to determine the performance of the model in correcting the ionospheric delay.

2. The NeQuick model

2.1. Standard NeQuick model

The climatologic ionospheric model NeQuick reproduces TEC along a given ray path as well as electron density distributions for a given month, geographic latitude and longitude, height and UT, giving the potentiality for ground-satellite as well as satellite-satellite link corrections. The model uses the Epstein formulation for the bottom side ionosphere and a simple formulation (Semi-Epstein layer), with a thickness parameter increasing linearly with height. NeQuick is based on a set of ionogram parameters (CCIR[1] coefficients). The two major components of the model are: The bottom side model for the height region below the peak of the F2-layer and the top side model for the height region above the F2-layer peak. It also requires the monthly mean of solar radio flux at about 10 cm wavelengths (F10.7) as an additional input parameter. The F10.7 index is a measure of the solar activity, the noise level generated by the sun at a wavelength of 10.7 cm at the earth's orbit. It has been found to correlate well with the sunspot number (Rz). The sunspot number is defined from counts of the number of individual sunspots as well as the number of sunspot groups. The F10.7 index can be measured relatively easily and quickly and has replaced the sunspot number as an index of solar activity for many purposes. It can be used as a daily index or averaged over longer periods (typically averaged over a month or a year although sometimes a 90 day average is made) to trace out the trends in solar activity. The correlation between these quantities is evident but there is still considerable scatter even for monthly-averaged values. The following equations are useful for converting between the F10.7 index (F10.7) and sunspot number (Rz). The equations are valid on a statistical (i.e. average) basis.

[1] Comité Consultativ International des Radio communications (CCIR)

$$F10.7 = 67.0 + 0.572\ Rz + (0.0575\ Rz)^2 - (0.0209\ Rz)^3 \quad (1)$$

$$Rz = 1.61\ FD - (0.0733\ FD)^2 + (0.0240\ FD)^3 \quad (2)$$

where, FD = F10.7 - 67.0.
A full description of the model can be found in [10] as well as the NeQuick model source code.

2.2. Optimisation description of the NeQuick model

To generate the GALILEO ionosphere corrections for single frequency receivers using NeQuick, the following procedure should be followed (as proposed by AG-IONO).
The first achievement is to optimise the NeQuick model as a function of the effective ionization level (Az) to the observed STEC values. The Az parameter (F10.7 corrected including the latitudinal dependence) is the driver for the model optimization to the reference measurements at the selected monitor stations. For every station, all the satellite links are taken into account and the sum of squares of observed minus computed STEC are calculated:

$$(\Delta STEC)^2 = \sum_{GPSlinks} \left| STEC_{Observed}(Az) - STEC_{Modeled}(Az) \right|^2 \quad (3)$$

$STEC_{Observed}$ values from each IGS monitor station to every satellite in view are needed. In this work, two different sources of STEC data are used: STEC values from IFAC and from IGS[2] Ionospheric maps. These Global Ionospheric Maps (GIMs) are computed by four IGS Associate Analysis Centres (IAACs) being nowadays CODE, ESA, JPL and UPC[3], on a daily basis (available at ftp://cddisa.gsfc.nasa.gov/gps/products/ionex/*year*/*doy*). After computation, three Validation Centers (JPL, ESA and UPC) validate them and combine them into a common IGS GIM (distributed with at least 12 days of latency, and presently rapidly as well within less than 24 hours) providing as well weights and external (dual-frequency altimetry-derived) TEC data. The global accuracy of this combine TEC is about 2-8 TECU (1 TECU corresponds to an ionospheric delay of 16 cm in L1) depending on the epoch in the Solar Cycle, season, latitude and proximity of available GPS receivers. We will use the available IGS vertical maps provided by the UPC agency, as an additional source of external STEC data for the present study.
$STEC_{Modeled}$ values along each ray path from receiver to satellite are calculated using the NeQuick model, as a function of the Az parameter.

The next step is to minimize $(\Delta STEC)^2$ as a function of the Az parameter, to find the optimum Az and thus defining the daily Az value for the station. This has been implemented at intervals of 24 hours and at a sampling rate of 20 minutes for data from IFAC and 15 minutes for data from IGS Ionospheric maps.
From (3), the expected shape is a parabola with a unique minimum. As a proof of this assumption, (3) was computed and plotted as a function of the Az parameter for all the IGS. A typical example is shown in the next figure.

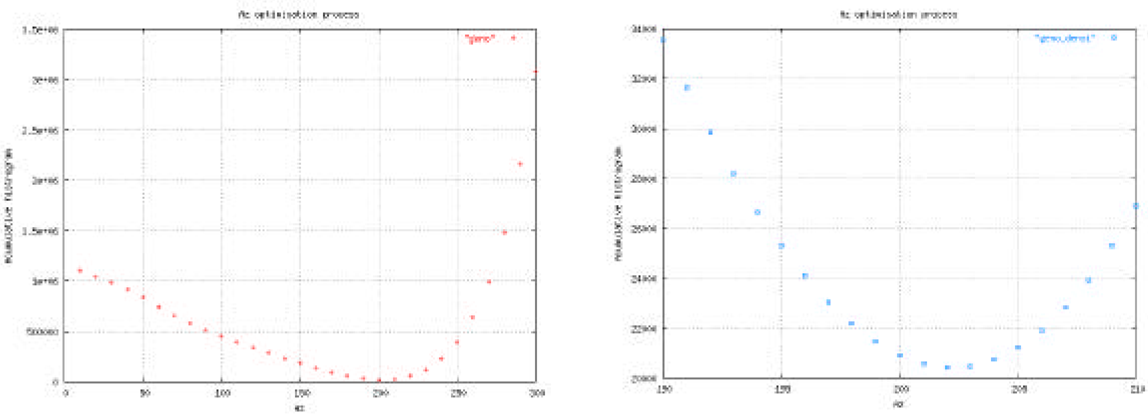

Figure 1: $(\Delta STEC)^2$ as a function of the Az parameter for IGS station marker name "geno". Right plot depicts a zoom of the minimum in left plot.

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2 International GPS Service for Geodynamics (IGS)

3 (CODE) University of Bern, Energy, Mines and Resources (EMR, NRCan), European Space Agency (ESA), Jet Propulsion Laboratory (JPL) and Polytechnical University of Catalonia (UPC).

From the daily Az values for every station, a global daily Az function of MODIP is found. This function is a second order polynomial described by three coefficients:

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

where:

$$\tan m = \frac{I}{\sqrt{\cos f}} \tag{5}$$

and μ stands for the modified dip or MODIP, I for the true magnetic dip and ϕ for the geographic latitude. The coefficients a_0, a_1, a_2 are transmitted to the user in the navigation broadcast message.

3. Performance tests

3.1. Comparison with TOPEX

The aim of this preliminary work is to show the performance of different approaches to the calculation of the GALILEO-like ionosphere corrections for a GNSS single-frequency user. The reference consists of the TOPEX/Poseidon data for the day of the study, 3rd March 2000. These data come from an altimetric satellite, at a mean height of about 1330 km. Among other sensors, it has a dual transmitter–receiver in C-band (5.5 GHz) and Ku-band (13.6 GHz), that provide total electron content (TEC) with accuracies, including systematic biases, of about 2–3 TECU [6]. For our comparisons, the bias and rms of the models have been computed regarding the TOPEX data as:

$$BIAS = \langle TEC_{TOPEX} - TEC_{Modeled} \rangle \tag{6}$$

$$RMS = \sqrt{\left\langle \left(TEC_{TOPEX} - TEC_{Modeled} \right)^2 \right\rangle} \tag{7}$$

where TEC_{TOPEX} is the TOPEX TEC and $TEC_{Modeled}$ is the TEC calculated using the NeQuick model under the selected approach. In order to determine how well a single frequency user can correct the ionospheric delay, the NeQuick model has been compared with the TOPEX data for several approaches.

3.2. Comparison with differential ionospheric values after fixing phase ambiguities

It is evident in (3) that the $STEC_{Observed}$ used as an input, plays a crucial role in the optimization of the Az parameter, thus in the calculation of the ionospheric corrections for GALILEO. The Wide Area Real Time Kinematics (WARTK) technique has been used to test the precision of the STEC used as input by comparing with differential ionospheric values after fixing phase ambiguities. This technique uses two programs in parallel, a geodetic and an ionospheric [9] one, in order to fix the phase ambiguities to their integer values in the fixed stations, providing an accurate ionospheric correction to roving users. It uses the fact that the coordinates of the fixed stations are known, then, it is possible to fix the Bc ambiguity (free ionospheric combination ambiguity) to its correct value with a few cm error with the geodetic program. In addition, the ionospheric program runs, in parallel estimating precise ionosphere that allows the computation of a double difference STEC accurate enough. Then mixing both results it is possible to fix the carrier phase ambiguities, and then, to extract a double difference STEC, with a millimeter accuracy. In fact, the differential ionospheric corrections provided by WARTK after fixing ambiguities is less than 0.1 TECU, also for permanent stations separated by thousands of km, including equator, Solar Maximum and high geomagnetic conditions [12].

4. Data set description

The chosen day of study is the 3rd of March of 2000. The Kp index for this day is smaller than 2 thus the requirement to use only data from an unperturbed geomagnetic period is guaranteed. This is necessary to estimate the validity of the computed model coefficients.

Two different IGS monitor station distributions have been selected to perform the comparison: an initial set of 26 available receivers (left side of Fig. 2) mostly distributed in the Northern middle region and a better globally distributed dataset of 25 stations (right side of Fig. 2). This second set of IGS stations has been chosen closest to the potential location for GALILEO monitor stations in order to evaluate the NeQuick model as close as possible to the conditions of the GALILEO system.

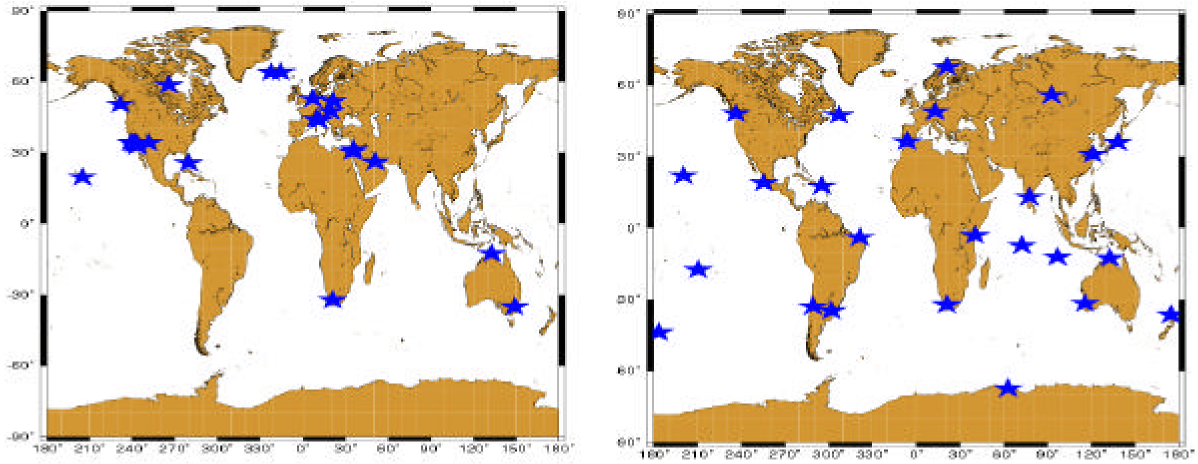

Figure 2: Selected distribution of IGS stations

5. Results

Several approaches have been explored such as different distribution of the monitor stations, different integration heights, an alternative way of deducing the Az values, and different input STEC values in order to study their impact on the results. They are displayed for every approach considering all latitudes and immediately after for latitude 40° to have a hint of the performance for our geographical situation. There are also depicted plots with a track of the TOPEX/Poseidon satellite versus the calculated values with the studied approach.

5.1. Influence of the geographical distribution of the monitor stations

The next table shows the results for the two depicted distributions of stations in Fig. 2. On the left distribution, one of the stations (receiver marker name: chur) had not data for the whole day and the global performance is significantly affected by considering or not this station in the calculation. The STEC data used as input are from IGS maps in the three cases.

	RMS (TECU)	% ERR	BIAS (TECU)	#Obs.	VTEC mean
IGS good distribution	16.42	42.9	11.23	51082	38.24
Latitude 40°	16.44	37.8	13.18	5047	43.54
IGS without chur	17.09	44.7	12.15	51082	38.24
Latitude 40°	17.31	39.8	14.30	5047	43.54
IGS with chur	18.25	47.7	13.56	51082	38.24
Latitude 40°	18.73	43.0	16.03	5047	43.54

Table 1: Results for different geographical distributions

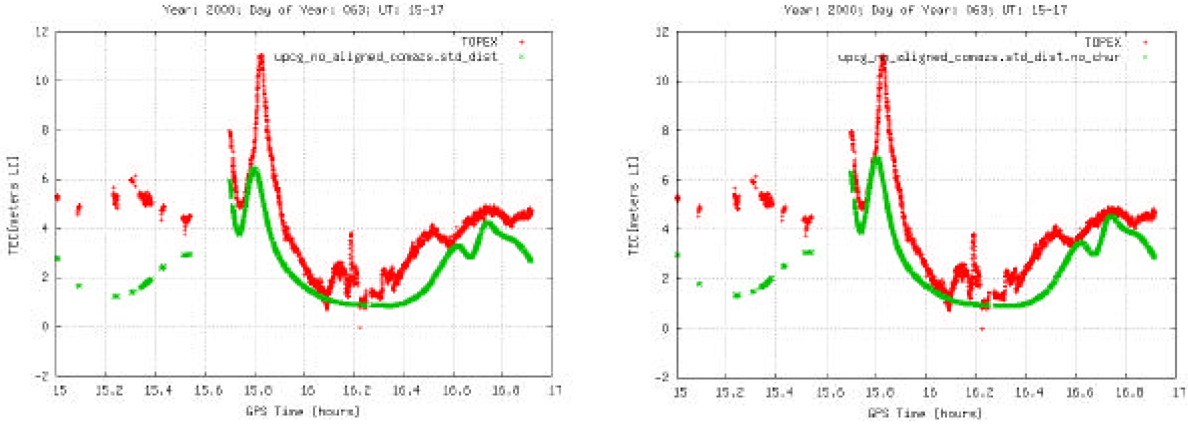

Figure 3: Even distribution with chur vs. TOPEX data and even distribution without chur vs. TOPEX

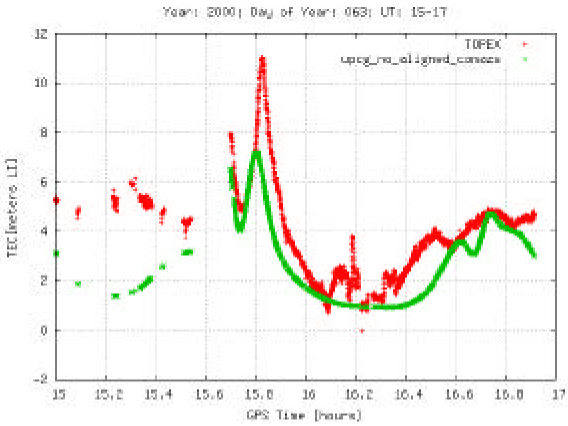

Figure 4: Uneven distribution vs. TOPEX

These results show that the quality of the performance is sensitive to the geographical distribution of input GNSS stations providing input STEC. The criterion for the station location choice should be to avoid uneven geographical distribution of stations.

5.2. Influence of the NeQuick plasmaspheric modeling

When considering the integration of the TEC along the receiver-satellite link, two integration heights have been chosen: on one hand, integrating up to the satellite current height and on the other hand, fixing the ceiling-height at 1300 km. This will give an assessment of the contribution of the plasmaspheric component of the NeQuick model to the final results. The STEC data used as input are from IGS maps in both cases.

	RMS (TECU)	% ERR	BIAS (TECU)	#Obs.	VTEC mean
1300 km	15.92	41.6	10.48	51082	38.24
Latitude 40°	15.75	36.2	12.25	5047	43.54
~ 20000 km	16.40	42.9	11.21	51082	38.24
Latitude 40°	16.42	37.7	13.15	5047	43.54

Table 2: Results for the different ceiling heights

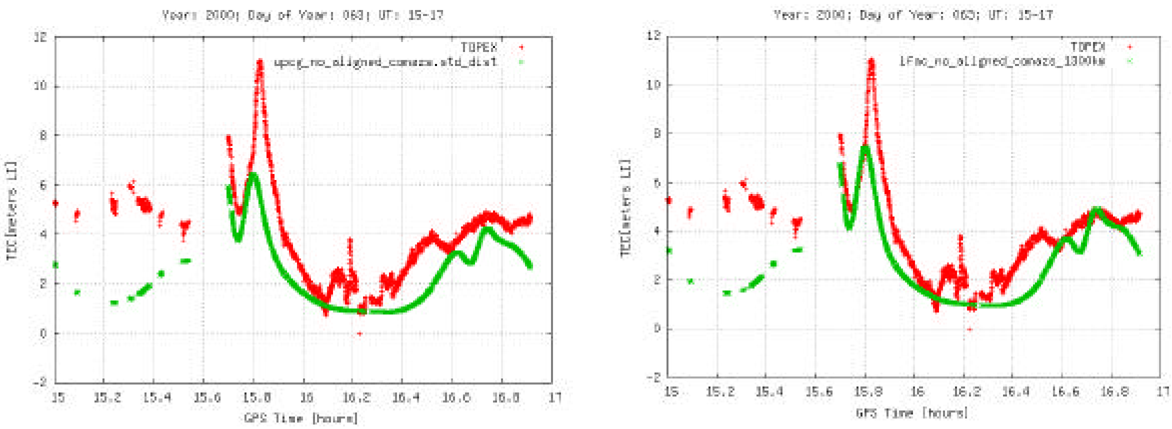

Figure 5: Ceiling-height at satellite position vs. TOPEX data and ceiling-height 1300 km vs. TOPEX data

The modeling of the plasmaspheric component (which is being improved by Cueto et al. 2004) has an influence in the performance: slightly better using NeQuick just to 1300 km (41.6%) in front of using to the GPS satellite height of 20200km (42.9%).

5.3. NeQuick model versus data driven model

Two quite different ionospheric modeling are compared: the GALILEO baseline model (NeQuick fed with approximately 25 stations data, adequate for real-time use) and the IGS ionosphere maps (computed only from GPS data, but including more than 100 stations, although not suitable nowadays for real-time use).

	RMS (TECU)	% ERR	BIAS (TECU)	#Obs.	VTEC mean
IONEX Latitude 40°	11.34 5.72	29.4 13.1	-2.32 -2.11	51082 5047	38.24 43.54
IGS good distribution Latitude 40°	14.50 13.05	37.9 30.0	6.96 7.96	51082 5047	38.24 43.54

Table 3: Results for the NeQuick model vs. IONEX

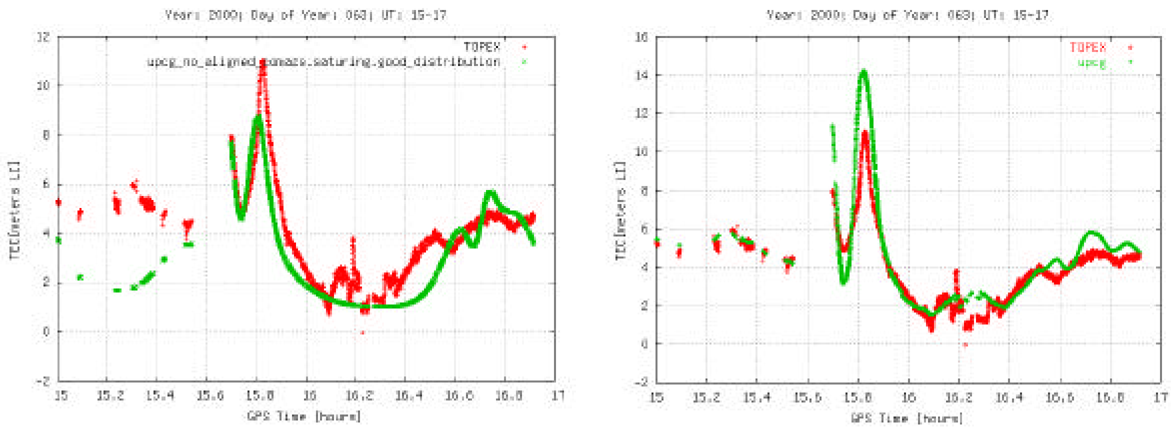

Figure 6: Uneven distribution vs. TOPEX and IONEX vs. TOPEX

The IGS ionosphere global maps show a better performance as it could be expected.

5.4. NeQuick model versus Klobuchar model

The Klobuchar model is a so-called ionospheric single-layer model, meaning that the ionosphere is approximately reduced to an infinitesimal thin layer modelling the vertical electron content of the ionosphere. The model allows an approximation of the propagation delay for signals, which cross the ionosphere in vertical direction. At night times the delay is set to a constant value of 5 ns, at day times the delay is modelled by a cosine function of the local time. Amplitude and period of the cosine function are dependent on the geomagnetic latitude of the sub-ionospheric point. These quantities can be computed by the use of 8 coefficients uploaded daily to the satellites and broadcast to the user. A detailed description of the model can be found in the public GPS ICD document [8]. The literature states that the Klobuchar model includes only 50 % of the ionospheric delays. The full algorithm for this ionospheric correction model Klobuchar is given by [8].

	RMS (TECU)	% ERR	BIAS (TECU)	#Obs.	VTEC mean
IGS good distribution Latitude 40°	14.50 13.05	37.9 30.0	6.96 7.96	51082 5047	38.24 43.54
Klobuchar Latitude 40°	15.63 11.78	40.9 27.0	5.48 -4.01	51082 5047	38.24 43.54

Table 4: Results for the NeQuick model vs. the Klobuchar model

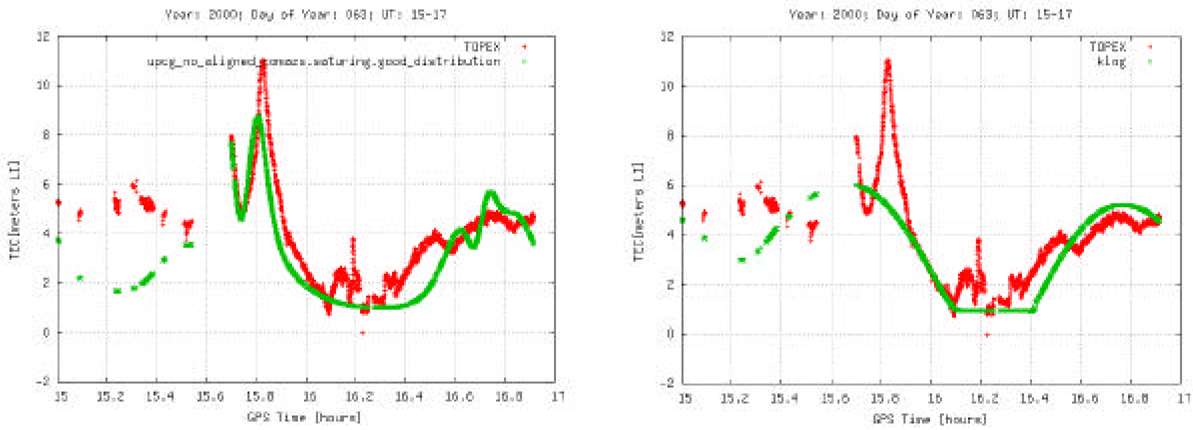

Figure 7: NeQuick vs. TOPEX data and Klobuchar vs. TOPEX

The Klobuchar model broadcasted by the GPS navigation message provides worst results at global scale for the NeQuick approach shown: 41% in front of 38% of NeQuick (adjusted with 25 globally well distributed stations). On the other hand, the results for this day of study indicate that Klobuchar performs better for mid-latitudes.

5.5. Alternative calculation of Az

An alternative way of optimizing the Azs is explored in this work, consisting on an independent optimization per each satellite-receiver link instead of one daily optimization. This procedure is faster in terms of calculation time.

	RMS (TECU)	% ERR	BIAS (TECU)	#Obs.	VTEC mean
Standard procedure Latitude 40°	16.40 16.42	42.9 37.7	11.21 13.15	51082 5047	38.24 43.54
Ray by ray optimization Latitude 40°	16.67 16.79	43.6 38.6	11.59 13.63	51082 5047	38.24 43.54

Table 5: Results for the standard vs. ray-by-ray optimization procedures

Table 5 shows that it is slightly worst (43.6% in front of 42.9%). Nevertheless, this fast approach provides the capability to study the Az evolution in terms of local time (see Fig. 8 for IGS –left- and IFAC –right- input STEC) in front of the global-per-station Az adjustment.

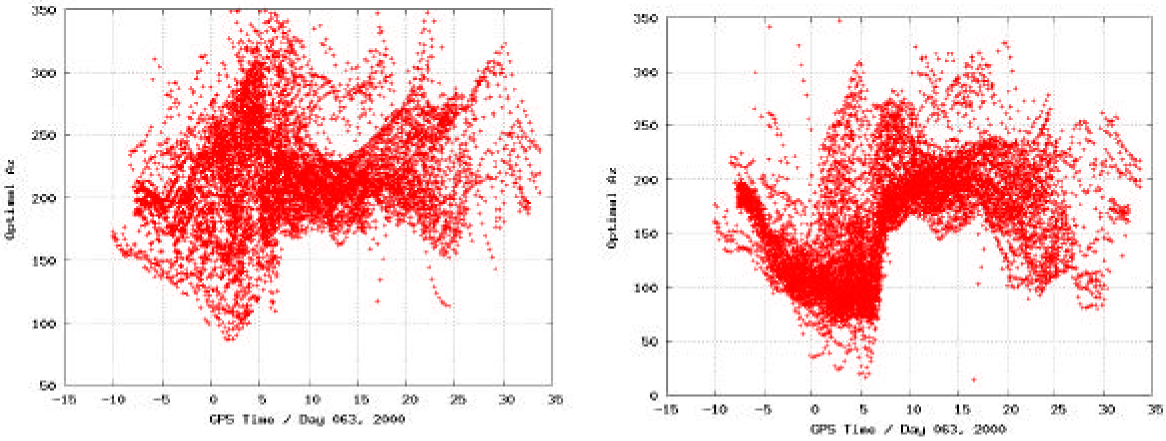

Figure 8: Az evolution in terms of local time (IGS and IFAC input reference STEC)

It can be observed in Fig. 8 a quite compatible Az during the daytime and important discrepancies in the night. The three coefficients determining the Az variation with MODIP were designed to be broadcasted to the user in the navigation message updated at least once every 24 hours. The evolution of Az with local time in Fig. 8 could indicate the need to reduce the interval between broadcasts to 12 or even 6 hours.

5.6. Influence of different input STECs sources

Two different input STEC reference have been compared: STEC values from IFAC and from IGS Ionospheric maps.

	RMS (TECU)	% ERR	BIAS (TECU)	#Obs.	VTEC mean
IGS input STECs	15.83	41.1	1.89	51082	38.24
Latitude 40°	11.55	26.5	1.76	5047	43.54
IFAC input STECs	16.67	43.6	11.59	51082	38.24
Latitude 40°	16.79	38.6	13.63	5047	43.54

Table 6: Results for IGS input STECs vs. IFAC input STECs

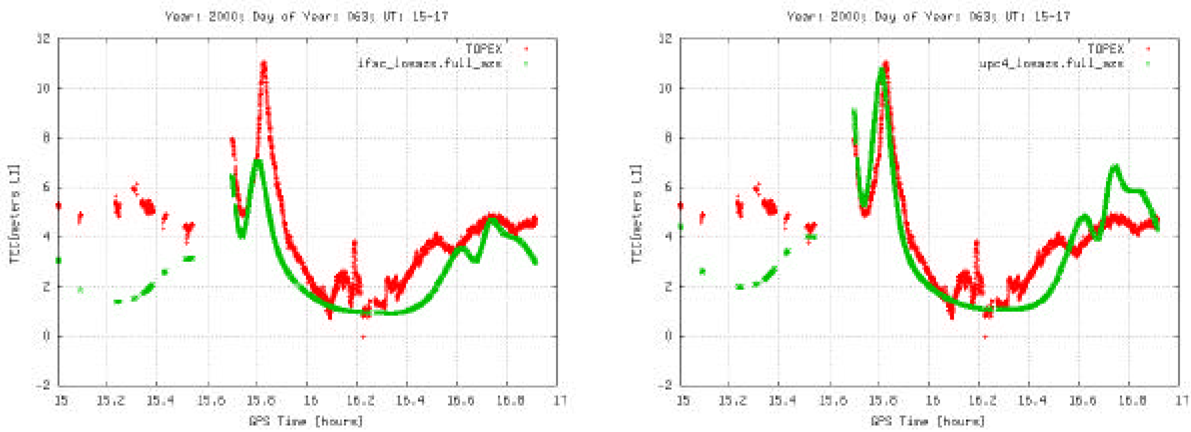

Figure 9: IFAC input STEC vs. TOPEX and IGS input STEC vs. TOPEX

The approach is sensitive to the input STECs: during this day, the IGS input STECs perform better from both the TOPEX vertical ionospheric and the differential ionospheric assessments as indicates Fig.10.

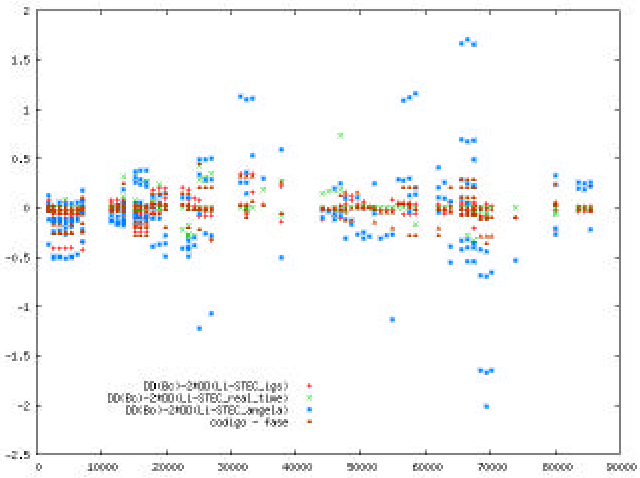

Figure 10: In blue, differential ionospheric error using IFAC STECs and in red, differential ionospheric error using IGS IONEX STECs

6. Conclusions

In this study, the first results of the performance of the GALILEO-like ionospheric corrections for single frequency users have been shown computed by adjusting the NeQuick model to ionospheric observations of different nature in a set of worldwide distributed GPS stations of the IGS network.

The main performance metrics used have been the comparison to dual-frequency TOPEX altimeter observations. Such observations, gathered on the 3rd of March of 2000 under Solar Maximum conditions, are worldwide distributed over the oceans, and typically far from GPS stations.

The main conclusions of this preliminary study are referred to the sensitivity of the quality of the GALILEO-like ionospheric corrections to:

- The geographical distribution of the monitoring reference stations. The performance improves with a better globally geographical distribution of stations.
- Maximum allowable ceiling height: limiting it performs better, being compatible with the potential improvements to be done in the plasmaspheric NeQuick modeling reported by several authors.
- A certain explored NeQuick approach seems to perform slightly better than the Klobuchar model (with eight broadcasted coefficients) at global scale, and worst than the only-data IGS ionospheric maps (computed from more than 100 receivers, instead of 25).
- Input STEC quality to adjust NeQuick (IGS Ionospheric Maps performs better for the selected day).

Furthermore, an alternative way of adjusting Az has been tested that could be useful for exploring the consistence of the daily Az adjustment approach, and open the possibility to a potential increase of the temporal resolution of the broadcast of the coefficients a_0, a_1, a_2.

These performance tests and preliminary results (obtained from one single day of data) should be extended to a significant period of time. The study should consider the error from the user point of view, with the predicted a_0, a_1, a_2 values broadcasted for the following day.

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