Impact of NeQuick Correction Model to Positioning and Timing Accuracy using the Instantaneous Pseudo Range Error of Single Frequency Absolute Positioning Receivers

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BIOGRAPHY

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ABSTRACT

The ionospheric delay for GNSS is an effect difficult to predict and thus difficult to model. The Klobuchar model which is the standard correction model for single frequency GPS receiver has its limitation: it can only correct 50% of the global ionosphere error. The NeQuick model is a good candidate to be the standard ionospheric model for single frequency Galileo receivers. Thanks to the concept of IPRE developed in [1], it is possible to predict the performances of the NeQuick model using different configurations, in the case the ionosphere error is the dominant one and in the case it is not the dominant one. This paper describs the results by presenting a comparison using the first two statistical moments: the mean and the variance. The time series are providing interesting results especially when looking at some seasonal effects which in the case of NeQuick tends to be reduced and tend to center the distribution of the ionosphere residual error.

INTRODUCTION

This paper analyzes the results obtained from 4 IGS stations (”nya1” in Norway, ”pots” in Germany, ”lhas” in China and ”fort” in Brazil) during the year 2000. After defining the field of our study and the main characteristics of the Klobuchar and NeQuick models, we will recall the concept of IPRE and the relation between the pseudo range error and the position error.

A first set of results will represent the time series analysis of instantaneous ionospheric error during the year 2000 (year of maximum solar activity) for both Klobuchar and NeQuick correction models, a comparison will be led at pseudo-range level and at position level.

A second set of results will analyze the impact of the ionospheric correction model at the global pseudo range level and then at the global position error level. During the first 5 months of year 2000 the Selective Availability (SA) was switched on. this specific condition will be used to see the impact of the ionospheric correction model when ionospheric error is not the dominant one. Along this paper, we represent the performances using the first two statistical moments which is for performance analysis not sufficient but coupled with the estimated probability distributions, it is possible at least to give the availability of this approximation: If the distribution can be considered visually as Gaussian, bias and sigma parameters are sufficient to characterize the performances of a considered scenario. In any other case, one should be careful with the conclusions one can draw. The comparison of the statistical parameters of the ionospheric error for different geographic locations will give us the opportunity to analyze the performances of ionospheric correction model function of the location of the user. We will conclude by discussing the performances expected for the use of NeQuick model for Galileo single frequency receivers.

FIELD OF STUDY

The year 2000 has been taken as our simulation period. In order to study different impact of ionospheric regions, one IGS station has been chosen in the equatorial region (fort in Brazil), one in a low latitude region (lhas in Singapore), one has been taken in the polar circle (nya1 in Norway) and another one in Germany (pots). The year 2000 has been selected because it corresponds to a maximal solar activity. A sampling period of one hour has been chosen for each individual error and thus also for the global error.

Table 1 IGS locations

Code	Country	Latitude	Longitude	Altitude
pots	Germany	52.4^o	13.1^o	174m
nya1	Norway	78.9^o	11.9^o	84m
lhas	China	29.7^o	91.1^o	3622m
fort	Brazil	-3.88^o	322^o	20m

Table 2 Measurement assumptions

Error	Estimation	Reference	Sampling period
Clk	RINEX NAV	SP3	1 hour
Eph	RINEX NAV	SP3	1 hour
IonK	Klobuchar model	L1L2*	1 hour
IonN	NeQuick model	L1L2	1 hour
Trop	MOPS model	SINEX	2 hours
MN	–	TEQC	1 hour

*For Ionospheric error, the use of both observations in L1 and L2 permits to extract the slant TEC choosen as reference.

Tab. 2 represents the assumptions used to produce the individual errors for GPS. By defining the error as a reference minus a correction.
where Clk is the satellite clock error,
Eph is the ephemeris error,
Iono is the ionospheric error,
Trop is the tropospheric error,
MN is the multipath and receiver noise error,
IONEX are the post processing files obtained from IGS stations of the vertical total electron content all over the world sampled every two hours.
SINEX are the post processing files obtained from IGS stations and providing every two hours for the IGS location concerned the zenith tropospheric delay.
RINEX NAV are the navigation files broadcast by satellites for the considered period of measurement, SP3 are the post processing precise clock delay and satellite orbits provided every 15 minutes for each GPS satellite.
For multipath and noise error, we used the TEQC program developed by the UNAVCO community.

THE KLOBUCHAR AND THE NEQUICK MODELS

The Klobuchar model

This model is a ionospheric single layer model. The TEC is supposed concentrated in an infinitely thin layer at a given altitude (350 km). A constant ionospheric delay of 5 ns is taken for the night period. During the day a cosine function of the location is used whose amplitude and period are depending on the geomagnetic latitude of the sub-ionospheric point. The α and β coefficients (4+4) used to complete the model are daily broadcast by the satellites. For the description of this model see [2].

The NeQuick model

This 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 [3]. NeQuick is based on a set of ionogram parameters (CCIR coefficients). It requires the monthly mean of solar radio flux at about 10 cm wavelength (F10.7) as an additional input parameter. The two major components of the model are [1]: 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. For the application in Galileo the F10.7 model input parameter, that can be seen as the driver of the model, is replaced by the so called effective ionization parameter Az. Az itself is a function of the modified dip latitude ”Modip” m : $Az = a_0 + a_1 \times m + a_2 \times m^2$

The three coefficients of this second order polynomial are the foreseen ionospheric navigation message parameter in the future Galileo. For our study we have crated these parameters by optimizing the NeQuick model (according to the procedure described in [4]) to a set of about 30 global distributed IGS stations which reflect the distribution of the future Galileo monitor stations. Then these parameters have been applied at our selected reference stations to generate the NeQuick corrections. For a detailed description of this model and the generation of the NeQuick parameter see [5] [6] and [7].

IPRE CONCEPT AND POSITION ERROR

IPRE concept

Let’s recall the fundamental error equation for a single frequency receiver [8]:

$$\overline{\Delta\rho} = c\cdot\left(-\overline{\Delta B}+\overline{\Delta I}+\overline{\Delta T}+\overline{\nu}\right)+\overline{\overline{\epsilon}}\cdot\left(\overline{\widehat{R}}-\overline{\widehat{P}}\right)+\overline{\overline{A}}\cdot\overline{\Delta R} \tag{1}$$

where

$\overline{\Delta\rho} \equiv \overline{IPRE}$ is the vector of instantaneous pseudo-range errors corresponding to the observable satellites,

$c \cdot \overline{\Delta B} \equiv \overline{Clk}$ is the vector of satellite clock errors,

$\overline{\overline{\epsilon}} \cdot \left(\overline{\widehat{R}}-\overline{\widehat{P}}\right) + \overline{\overline{A}} \cdot \overline{\Delta R} \equiv \overline{Eph}$ is the vector of ephemeris errors,

$\overline{\overline{\epsilon}}$ is a matrix containing the errors in unit vectors of user to satellites,

$\overline{\widehat{R}}$ is the vector of estimated position of satellites,

$\overline{\widehat{P}}$ is the vector of estimated position of the user,

$\overline{\overline{A}}$ is a matrix containing the unit vectors of user to satellites,

$\overline{\Delta R}$ is the vector of the satellite position error,

$c \cdot \overline{\Delta I} \equiv \overline{Iono}$ is the vector of ionospheric errors,

$c \cdot \overline{\Delta T} \equiv \overline{Trop}$ is the vector of tropospheric errors,

$c \cdot \overline{\nu} \equiv \overline{MN}$ is the vector of multipath and receiver noise errors,

$\overline{\overline{X}}$ is the matrix notation,

$\overline{X}$ is the vector notation.

For more details see [1].

With our notations this error equation can be written as follow:

$$\overline{IPRE} = -\overline{Clk} + \overline{Iono} + \overline{Trop} - \overline{MN} + \overline{Eph} \tag{2}$$

Impact on position error

the relation between the pseudo range and the position error is given by the following equation:

$$\overline{IPRE} = \overline{\overline{G}}\cdot\overline{\Delta x} \Rightarrow \overline{\Delta x} = \left(\overline{\overline{G}}^{T}\overline{\overline{G}}\right)^{-1}\cdot\overline{\overline{G}}^{T}\cdot\overline{IPRE} \tag{3}$$

where $\overline{\overline{G}}$ is the geometry matrix as defined in [1] and $\overline{\Delta x}$ is the 4×1 vector of position error (the 4^{th} coordinate corresponding to the error on the receiver clock bias.

If we set

$\left(\overline{\overline{G}}^{T}\overline{\overline{G}}\right)^{-1}\cdot\overline{\overline{G}}^{T} \equiv \overline{\overline{H}}$

We use the ”all in view” method to determine the position of the user. By linear distribution we obtain:

$$\overline{\overline{H}}\cdot\overline{IPRE} = -\overline{\overline{H}}\cdot\overline{Clk}+\overline{\overline{H}}\cdot\overline{Iono}+\overline{\overline{H}}\cdot\overline{Trop}-\overline{\overline{H}}\cdot\overline{MN}+\overline{\overline{H}}\cdot\overline{Eph} \tag{4}$$

where each element of the second member represents the contribution of an individual error to the global position error.

THE IONOSPHERIC ERROR AT PSEUDO RANGE AND AT POSITION ERROR LEVEL

In this section are represented the residual ionospheric errors vs. time and their probability distribution functions for one year of measurements. The principle used to produce these residuals is to consider the ionospheric delay determined by dual frequency measurements corrected in one case by the Klobuchar model and in the other case by the NeQuick model.

The ionospheric error at pseudo range level

As an example we represent the results of nya1 (Norway) for the plot of the ionospheric error versus time. In Fig. 1 and Fig. 2 are represented the time series of the ionospheric error using for the first one the Klobuchar model for correction and for the second one using the NeQuick model. Here are considered all the satellites on visibility for each time step (every one hour) of the year 2000. Each satellite is represented by one specific color. As expected, the colors are mixed and a general evolution can be observed which is characteristic of a spatial correlated effect. This effect can be well observed for the ionospheric error corrected with the Klobuchar model for which a short seasonal dependency can be observed. For Klobuchar correction model, we can observe during winter an important positive bias which is not the case for the ionospheric error corrected by the NeQuick model. Nevertheless this effect is compensated a little bit during the Summer period. That is why considering a statistical analysis of one year measurements, this effect can be hidden. That is what is observed in the Probability density functions see Fig. 3 for which the complete period of one year has been taken and the statistical analysis took into account all the observations for each time step.

The results of bias and standard deviation corresponding to one year measurements are not representative of what the receiver would experience instantaneously but they give a tendency. In each x axis labels of time series graphics are represented the mean and the standard deviation calculated using all satellites on visibility at each time step for the complete period of measurements. The ionospheric error corrected with NeQuick model show a higher bias (0.92

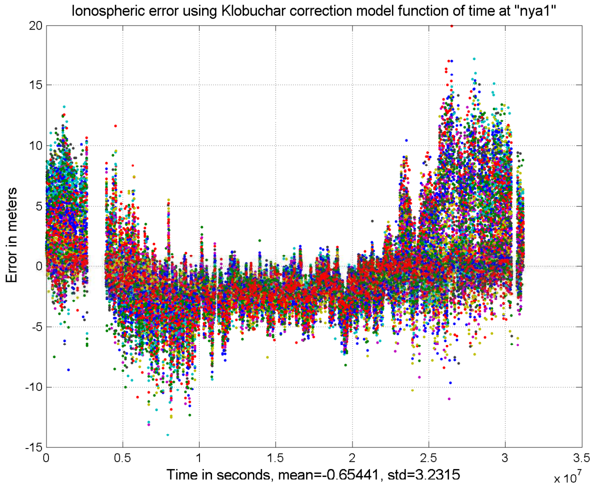

Fig. 1 Time series of ionospheric error using Klobuchar model

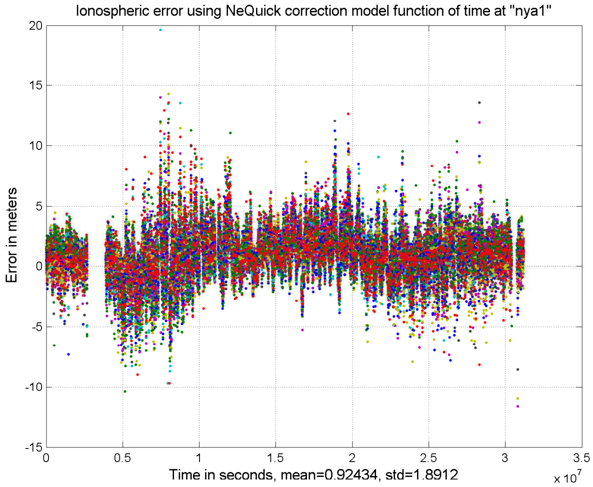

Fig. 2 Time series of ionospheric error using NeQuick model

meter $>$ 0.65 meter) than for the ionospheric error corrected by the Klobuchar one. But the standard deviation is almost 2 times greater for Klobuchar than for NeQuick model (resp. 3.23 and 1.89). In fact what we explained above concerning Winter and Summer variations has been interpreted as a fluctuation (standard deviation) in a one year measurements than as a bias. In fact depending on the sub period considered (one season), these results would be different. On the contrary, Klobuchar model presents less standard deviation during the summer than the NeQuick model. The same remark can be drawn. For a global analysis, it has been chosen to stay at a one year level of statistical analysis. Nevertheless, the analysis of both time series and probability density functions give us a maximum of information and this representation will be used in the whole document.

NeQuick has the advantage to correctly represent the seasonal fluctuations (observed in the 3 other IGS stations).

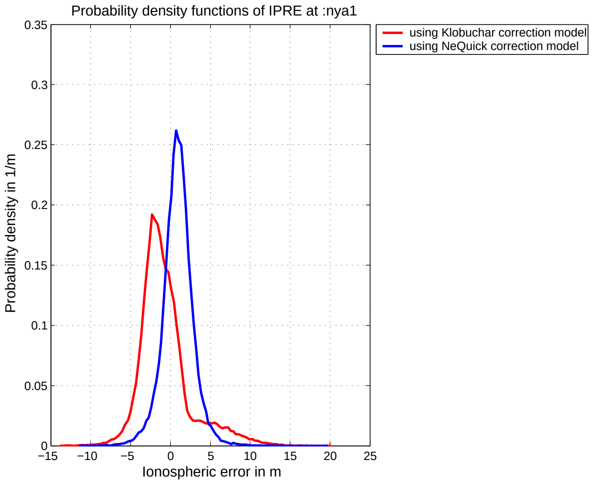

Fig. 3 Probability densities of ionospheric error

From the Fig. 3, we can observe that the distribution of the residual ionospheric error using NeQuick model is more sharp than the residual error using Klobuchar model. We can also observe a more Gaussian like distribution for NeQuick model than for Klobuchar model. The right part of the distribution curve of the residual error corrected by Klobuchar model seems to decrease less than the left part increases. This reflects the winter deviation of the residuals to the positive value (see Fig. 1).

Table 3 Statistical results for ionospheric error at pseudo range level

		pots	nya1	lhas	fort
Bias (m)	K(*)	0.253	-0.654	-2.467	-1.989
	N(*)	0.186	0.924	-0.930	-0.822
σ (m)	K	2.092	3.232	4.303	3.437
	N	1.711	1.891	3.261	3.428
RMS (m)	K	2.107	3.298	4.960	3.971
	N	1.721	2.105	3.391	3.525

(*) K for Klobuchar correction model and N for NeQuick correction model

From Tab. 3, the NeQuick correction model decrease the standard deviation of the ionospheric error of one year measurements. Concerning the Bias of ionospheric error, one can see that the bias in absolute value is decreased for ionospheric error using NeQuick model except for ”nya1”. The RMS values show a significant improvement using the NeQuick model. Nevertheless, the ionospheric error at the equatorial region is not so much reduced and this means that both models show some difficulties to fit the ionospheric delay at the equatorial region. Generally the

NeQuick model in comparison with the Klobuchar model gives for one year measurements an amelioration of both bias and standard deviation.
The next section will analyze the impact of the ionospheric error at the position level.

The ionospheric error at position level

In this section, we consider the position impacted by the ionospheric error in red using the Klobuchar correction model and in blue using the NeQuick correction model (this convention will be kept in the whole paper). The first two graphics show the 3D representation of the ionospheric error taking the delimitation of the axis to be equal to 4σ around the mean value (This convention will be used for all 3D graphical representations in the whole paper).

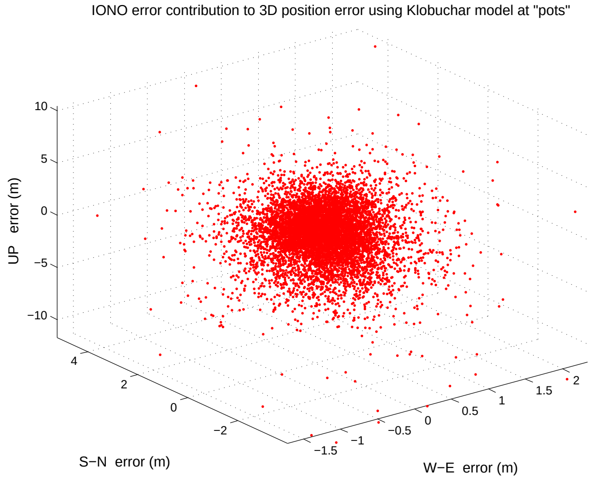

Fig. 4 Ionospheric error using Klobuchar model at position level

As expected from a previous study [1], the ionospheric error produces an elongation of the vertical error (one should pay attention to the scale of the axis). Here we represented the error at ”pots” IGS station in Germany. The representation in Fig. 4 and Fig. 5 shows the same results. But when observing the results from Fig. 6 to Fig. 8 a slight difference can be observed: First of all a shift along the S-N axis has been observed. By check in Tab. 4, this bias is observed at each station. Except for ”fort” and ”nya1” the NeQuick model tends to correct more the bias along this axis. Another remark concerns the sharpness of the distribution of error along the vertical axis. The ionospheric error distribution along the Up axis seems to have a smaller standard deviation by using the NeQuick correction model than by using the Klobuchar model. In Tab. 5, however, this reduction of the standard deviation is not so significant and can even be the opposite for ”fort”.

Concerning Tab. 4, the general comment we can give is a relatively low gain in the correction of the bias by using the NeQuick model. Except for ”lhas”, where a smaller bias has been observed in the 3 directions, the bias remains as important as for Klobuchar model.

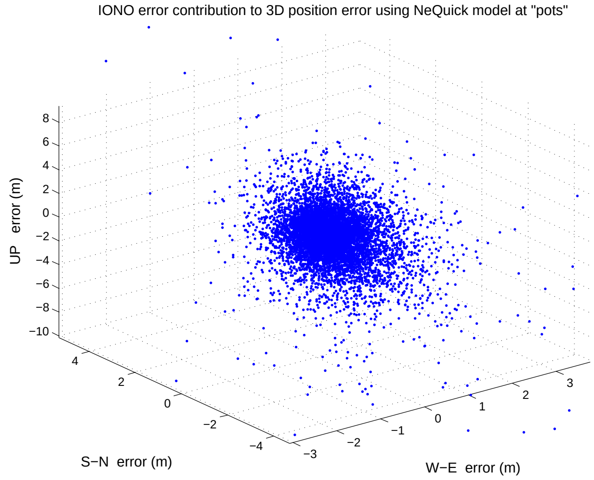

Fig. 5 Ionospheric error using NeQuick model at position level

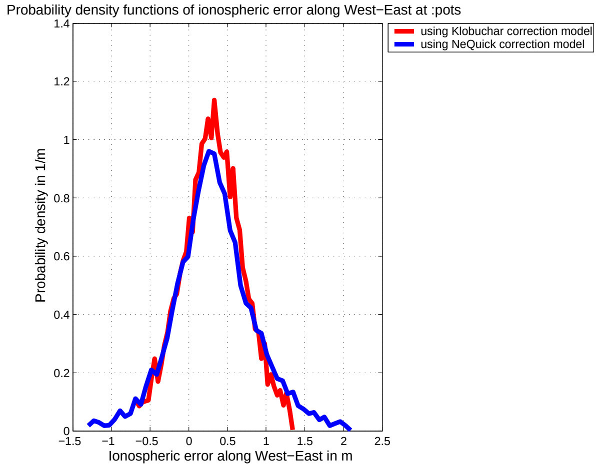

Fig. 6 Probability densities of ionospheric error along W-E axis

In Tab. 5, the same remark can be drawn. There is no real advantage of using the NeQuick correction model rather than the Klobuchar one. It can even be worse (for ”fort” for example).

In Tab. 6, and as a conclusion of this section, it has been observed that the ionospheric error corrected by the NeQuick model does not provide a significant improvement. But as observed in the ionospheric error vs. time, by taking into consideration the whole year 2000, the Klobuchar model shows difficulties to correct the ionospheric error at the beginning of the year and at the end (Winter) and this does not necessary appear in the statistical parameters of one year measurements.

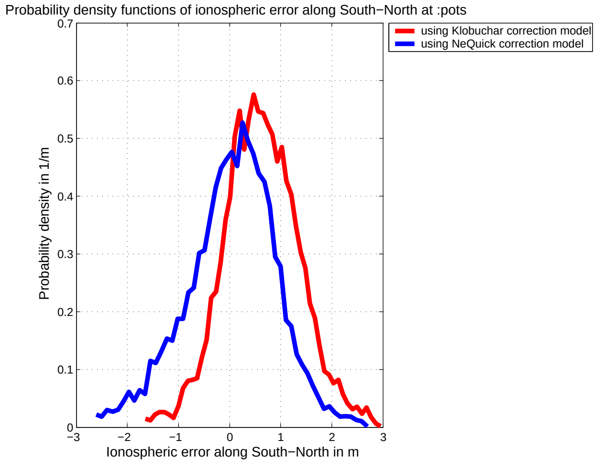

Fig. 7 Probability densities of ionospheric error along S-N axis

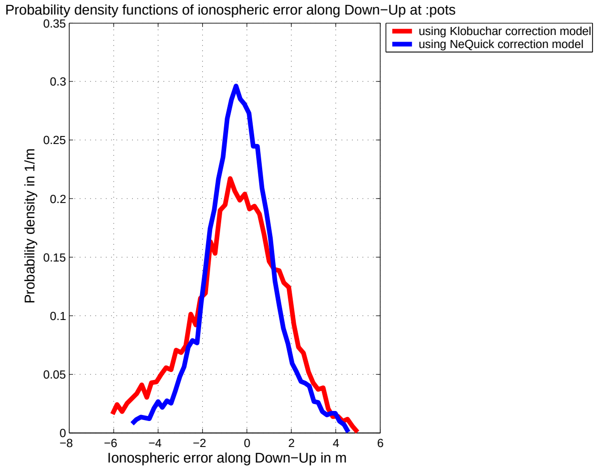

Fig. 8 Probability densities of ionospheric error along Up axis

IMPACT OF KLOBUCHAR AND NEQUICK MODEL IN THE GLOBAL ERROR

Table 4 Bias of ionospheric error at position level

		pots	nya1	lhas	fort
W-E (m)	K	0.311	0.301	-0.102	-0.057
	N	0.349	0.236	0.018	-0.316
S-N (m)	K	0.612	-0.137	3.129	0.631
	N	-0.014	-0.542	0.357	1.292
Up (m)	K	-0.629	0.105	1.489	1.997
	N	-0.385	-1.298	0.967	-0.596

Table 5 σ of ionospheric error at position level

		pots	nya1	lhas	fort
W-E (m)	K	0.507	2.034	2.440	5.160
	N	0.856	1.731	2.109	5.298
S-N (m)	K	1.153	1.635	4.413	5.027
	N	1.329	1.839	3.469	4.690
Up (m)	K	2.772	6.097	6.170	10.225
	N	2.440	5.557	5.681	10.871

This section deals with the ionospheric error corrected by the Klobuchar or NeQuick model associated with the five other sources of errors: The satellite clock error, the ephemeris error, the tropospheric error, the multipath and noise errors. As recalled in the introduction, until 2th of May, the SA was switched on and the magnitude of the clock error was multiplied by ten. In such conditions, the impact on the IPRE was so important that considering a whole year measurements would give unusable results. That's why the period is split into 2 sub periods one concerning the ”SA on” period: from the first of January 2000 to the 2th of May 2000 and another one corresponding to ”SA off” period: from 12th of August 2000 to the 31 of December 2000. The period corresponding to the 2th of May until the 12th of August was an ”unstable” period for the satellite clocks and so was not used in our study. When not specified, we will always consider the ”SA off” period in this section. The statistical results and the probability density function correspond of course to this period of observations.

Impact of Klobuchar and NeQuick model in the IPRE

Fig. 9 and Fig. 10 show clearly the 3 sub periods discussed above. Fig. 11 shows better results for NeQuick model than what we expected (see the conclusions of the previous section). It is not surprising because the periods of analysis are not the same and from the previous section, we saw that the Klobuchar model has difficulties to model the ionospheric delay at the end of the year 2000. The ”SA off”

Table 6 RMS of ionospheric error at position level

		pots	nya1	lhas	fort
W-E (m)	K	0.595	2.056	2.442	5.161
	N	0.925	1.747	2.109	5.308
S-N (m)	K	1.305	1.641	5.410	5.067
	N	1.329	1.917	3.487	4.865
Up (m)	K	2.842	6.098	6.347	10.418
	N	2.470	5.707	5.763	10.887

period correspond almost exactly to this. Thus, the IPRE corrected by the NeQuick model shows a more sharp distribution than the IPRE corrected by the Klobuchar model. Not only the standard deviation but also the bias is well corrected and that for all stations (see Tab. 7)

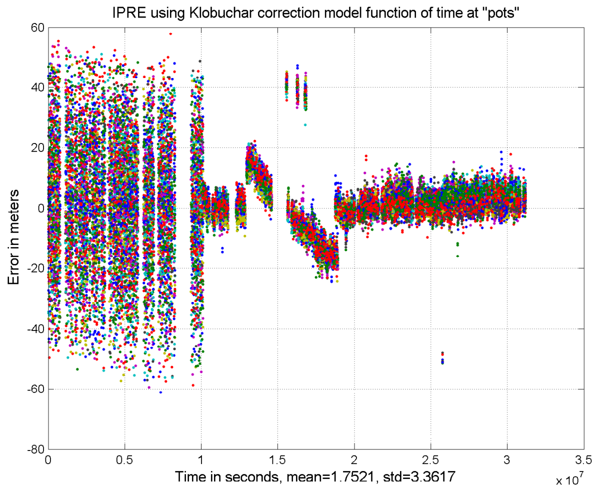

Fig. 9 Time series of IPRE error using Klobuchar model

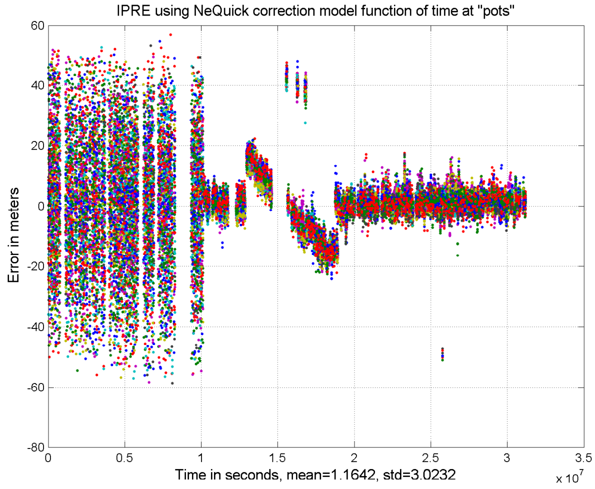

Fig. 10 Time series of IPRE error using NeQuick model

Impact of Klobuchar and NeQuick models in the position error

Here again, the "SA off" period is taken into account. The projection of the IPRE in the position level represents the positioning error the receiver will experience.

Fig. 12 and Fig. 13 represent the global position error at "lhas". These results don't show a significant difference between both correction models, but if we look at the probability density functions along 3 axis see Fig. 14 to Fig. 16, we observe a deviation in the S-N axis of the position error corrected by the Klobuchar model. A more sharp distribution for NeQuick model is observed in each direction.

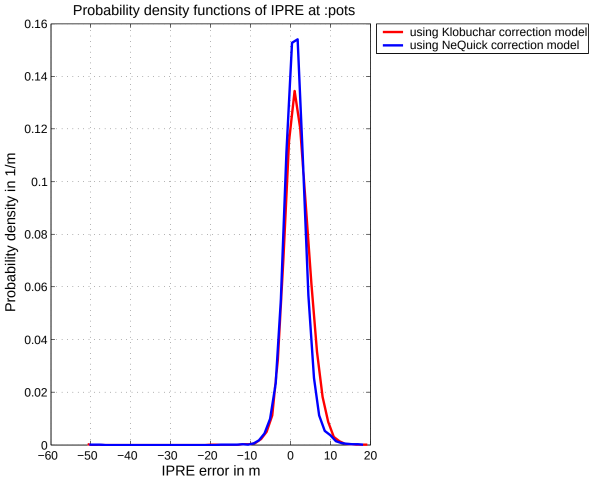

Fig. 11 Probability densities of IPRE

Table 7 Statistical results for IPRE at pseudo range level

		pots	nya1	lhas	fort
Bias (m)	K	1.752	2.077	-2.080	-1.905
	N	1.164	1.694	-0.671	-0.392
σ (m)	K	3.362	4.509	5.566	3.886
	N	3.023	2.706	4.509	3.428
RMS (m)	K	3.791	4.965	5.942	4.032
	N	3.240	3.193	4.559	3.450

Table 8 Bias of IPRE at position level

		pots	nya1	lhas	fort
W-E (m)	K	0.157	0.291	-0.322	-0.775
	N	0.171	0.065	-0.078	-1.006
S-N (m)	K	0.416	-0.565	4.654	0.786
	N	0.000	-0.475	1.056	1.104
Up (m)	K	-0.692	-3.518	2.615	1.124
	N	0.395	-1.420	2.398	-1.825

Tab. 9 shows a good bias correction of the bias in the N-S correction but seems not a generality for every station, for "fort" it is even the inverse. But except for "fort", the results show a general improvement of the bias by using the NeQuick model. Concerning the standard deviation, the results shows almost no differences. The same performances for Klobuchar and for NeQuick model are observed. In some directions, the NeQuick model is even worse. As a result, the RMS in each direction confirms the fact that the

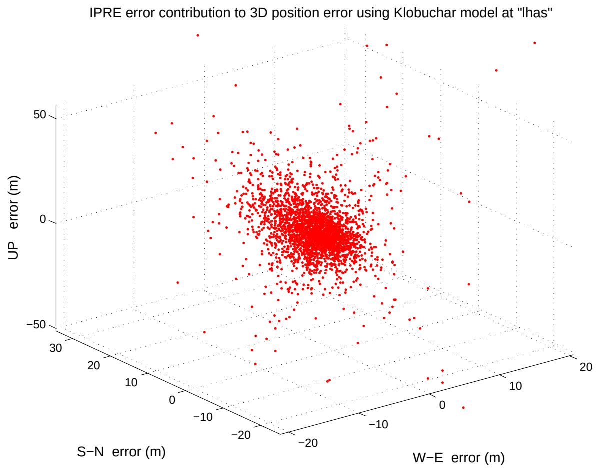

Fig. 12 IPRE using Klobuchar model at position level

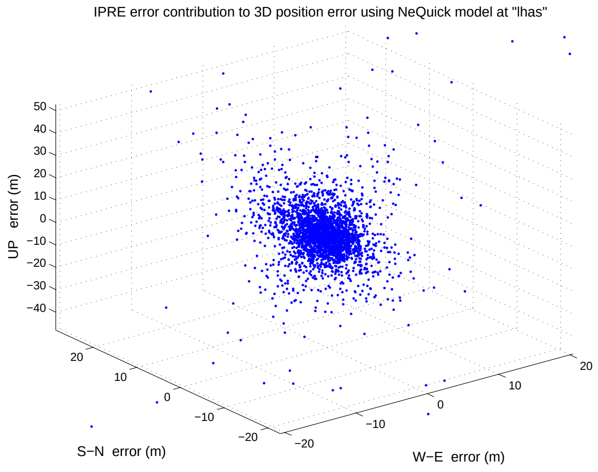

Fig. 13 IPRE using NeQuick model at position level

NeQuick model does not correct so much the global error. The geometry of the satellites in view tends to attenuate the advantage of the NeQuick model observed at the pseudo range level.

IMPACT OF KLOBUCHAR AND NEQUICK MODEL IN THE GLOBAL ERROR WITH SA ON

In the section before, even if the relative gain of the NeQuick model is low, it has been observed that there is still an amelioration of the position error by using the NeQuick model.

As discussed in the introduction, the SA will act as a dominant error and can be replaced by any other noisy error (multipath, receiver noise error ...) which could make the Ionospheric error not any more dominant. For a better comparison, we will consider measurements from the same station as in the previous section. For this study only the data until 2/05/2000 will be considered.

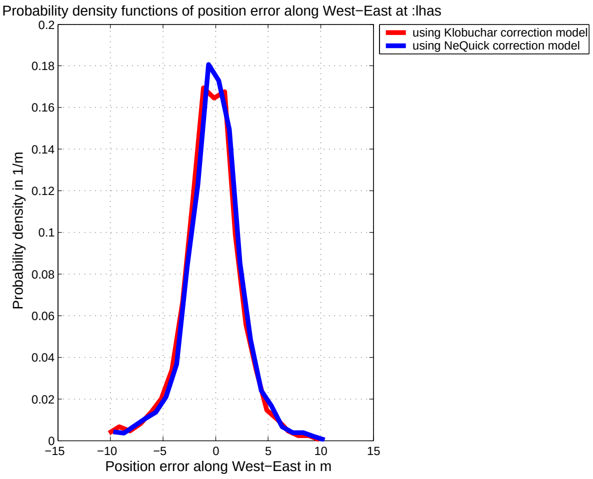

Fig. 14 Probability densities of IPRE along W-E axis

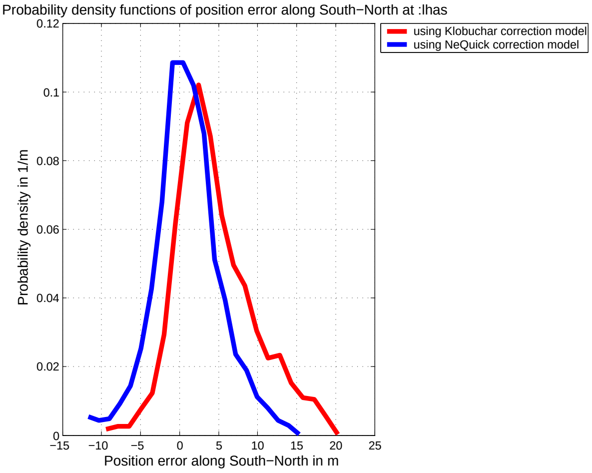

Fig. 15 Probability densities of IPRE along S-N axis

Impact of Klobuchar and NeQuick model in the IPRE with SA on

In this subsection, we won't represent the time series that have already been presented before. By comparing the statistical results, it is to be noticed that the major impact of the SA is in the standard deviation of the IPRE. This corresponds to the nature of the SA (addition of a centered noise to the satellite clock error). Tab. 11 shows a relatively big difference between biases. This confirms the results of [9] that even if the ionospheric error is not the dominant one, the residual ionospheric bias impacts the bias of the IPRE in the same way as if the ionosphere error was the dominant one (linearity of the bias operator). The standard deviation is for every station very high and of the same level of magnitude. The relative impact of the ionospheric error is almost nonexistent and so is the correction model.

Both PDF curves of Fig. 17 are almost superimposed. This

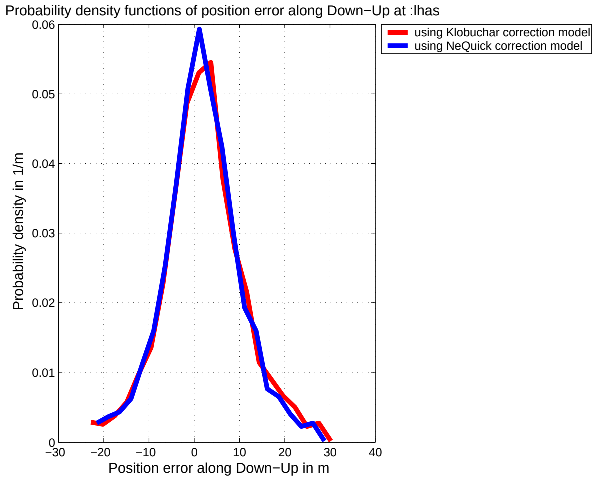

Fig. 16 Probability densities of IPRE along Up axis

Table 9 σ of IPRE at position level

		pots	nya1	lhas	fort
W-E (m)	K	2.943	5.573	5.204	6.014
	N	2.948	5.544	5.124	6.441
S-N (m)	K	6.026	6.034	7.449	3.425
	N	5.930	6.276	6.867	4.057
Up (m)	K	10.108	14.817	13.450	16.523
	N	9.970	14.166	12.610	16.379

is to be compared with Fig. 11, for which a more sharp distribution of the IPRE using NeQuick can be observed. In the pseudo range level, the impact of a correction model of an error which is not the dominant one is negligible. Nevertheless this remark concerns the standard deviation. It can be easily explained by the nature of the standard deviation itself (see [9]): the standard deviation is the root of a positive quadratic operator and therefore in the case of independent errors is the root sum squared of individual standard deviations. The individual error with the highest standard deviation will drive the standard deviation of the whole error. Even if it has not been observed in the studied cases, we can intuitively imagine the impact of a ionospheric error bias. Again from [9] where this special case has also been studied.

Table 10 RMS of IPRE at position level

		pots	nya1	lhas	fort
W-E (m)	K	2.947	5.581	5.213	6.063
	N	2.953	5.544	5.125	6.519
S-N (m)	K	6.040	6.061	8.784	3.514
	N	5.930	6.294	6.948	4.204
Up (m)	K	10.132	15.229	13.702	16.561
	N	9.978	14.237	12.836	16.480

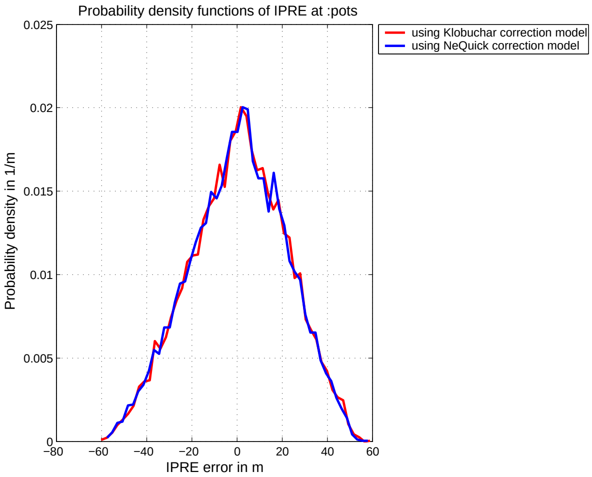

Fig. 17 Probability densities of IPRE

Table 11 Statistical results for IPRE at pseudo range level with SA on

		pots	nya1	lhas	fort
Bias (m)	K	0.756	0.489	-0.606	-6.252
	N	0.504	1.229	0.031	-4.574
σ (m)	K	21.340	22.185	21.293	20.697
	N	21.315	22.031	21.129	20.628
RMS (m)	K	21.353	22.190	21.302	21.621
	N	21.321	22.065	21.129	21.129

Impact of Klobuchar and NeQuick models in the position error with SA on

As a linear operator, the bias of an error even if it is not the dominant one will impact linearly the bias of the global error, therefore in any case, even when the ionospheric error is not the dominant one, the correction model should in priority reduce as good as possible the biases. The NeQuick model tends in almost every case to mitigate the error biases. Short period effects, should be well managed by the model. This is very important for short time scale applications like positioning of a dynamic user.

Tab. 13 compared with Tab. 9 shows a greater standard deviation of the position error. The results are more noisy and this is the consequence of the addition of the selective availability. This effect acts as an addition of a centered white Gaussian noise to the pseudo range measurements.

As the position is determined by a simple projection in a 3D space, the linearity of the process preserves the nature of the distribution. The position is also impacted with a 3D white Gaussian effect due to the selective availability. The dispersion of the points along the 3 axis coupled with a relatively low number of samples gives these fluctuations of the probability density functions. One should use more samples in order to smooth this effect. Nevertheless, it is still possible to explore these results. Obviously, as in the previous subsection, both curves of probability density functions are superimposed see Fig. 18 to Fig. 20. The x axis of these graphics doesn't permit to distinguish a shift (too big scale) but by looking at Tab. 12 there is a not negligible difference between biases along each axis.

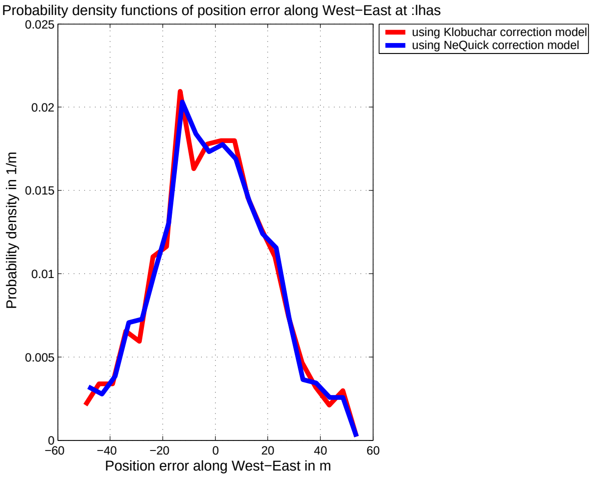

Fig. 18 Probability densities of IPRE along W-E axis

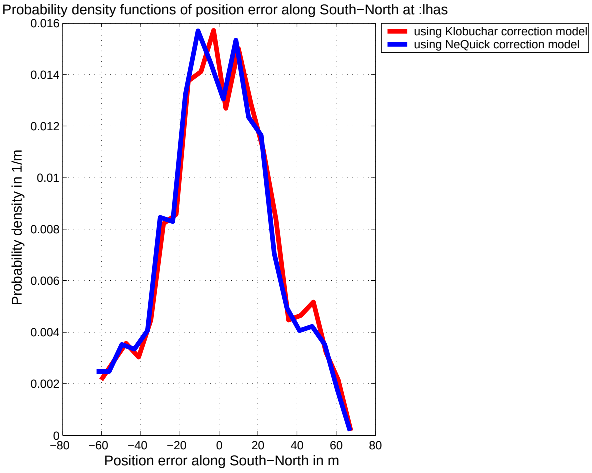

Fig. 19 Probability densities of IPRE along S-N axis

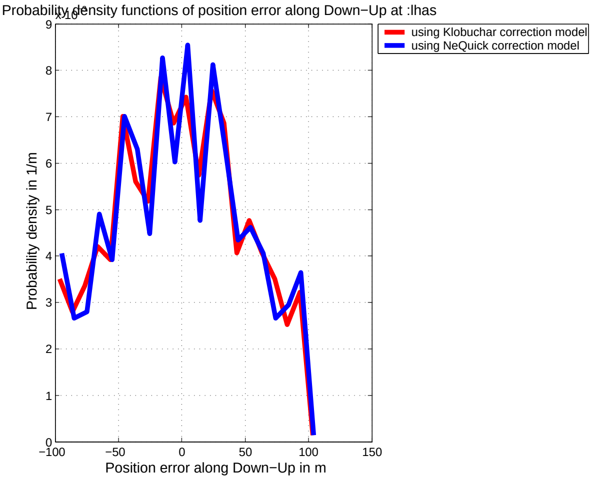

Fig. 20 Probability densities of IPRE along Up axis

Table 12 Bias of IPRE at position level with SA on

		pots	nya1	lhas	fort
W-E (m)	K	1.245	4.218	-0.160	2.099
	N	1.287	3.596	-0.176	1.554
S-N (m)	K	0.731	0.785	1.156	3.124
	N	-0.027	-0.812	-0.616	3.862
Up (m)	K	-0.311	11.783	-1.482	5.360
	N	0.189	15.307	-1.136	1.922

Tab. 13 shows a high level of standard deviation for both cases. The relative difference is negligible when compared to the relative difference of biases. These results should be consolidated by using a higher number of samples due as explained before to a too big dispersion of data. A possibility for that is to use a larger period of measurements and/or to use a smaller time step (rather than one hour between samples, one could use 15 minutes).

Tab. 14 resumes the results obtained and as expected the RMS value is principally dominated by the level of standard deviation. From these results and as a conclusion of this section, the NeQuick or any other correction model can improve the global accuracy by reducing the standard deviation only if the error corrected is the dominant one. But the way it handles the biases is even the most

Table 13 σ of IPRE at position level with SA on

		pots	nya1	lhas	fort
W-E (m)	K	22.790	31.662	25.968	27.723
	N	22.776	31.448	25.946	27.564
S-N (m)	K	32.844	22.237	32.425	29.207
	N	32.842	21.660	32.659	29.212
Up (m)	K	46.670	52.488	50.027	47.550
	N	46.525	56.066	50.210	49.590

Table 14 RMS of IPRE at position level with SA on

		pots	nya1	lhas	fort
W-E (m)	K	22.824	31.942	25.968	27.802
	N	22.812	31.653	25.947	27.608
S-N (m)	K	32.852	22.251	32.446	29.374
	N	32.842	21.675	32.665	29.466
Up (m)	K	46.671	53.794	50.049	47.851
	N	46.525	58.118	50.223	49.627

important for the global error, and for that by considering a shorter period of measurements, the NeQuick model tends to produce much stable results than the Klobuchar model, but this is also specific to the considered period of measurements which is in our case unfavorable for the Klobuchar model. This case should be investigated more in details in a future work.

CONCLUSION

This paper tries to give the performances of the NeQuick model under different configurations. Since this model is advised to be used as a correction model for Galileo single frequency receivers, some important points should be noticed. From the time series of the ionospheric error, it has been observed that the NeQuick model fit the best the real ionospheric delay. Linked with this remark, the bias seems to be reduced and the variance of the ionospheric error corrected by the NeQuick model gives in the major cases the lowest value. All these remarks impact the probability distribution function and tend to give a more centered Gaussian distribution with a relatively low standard deviation. Diluted in the global error, the difference between both models is attenuated. In the position level the geometry of satellites tends also to smooth these differences.

The bias and the standard deviation of errors are linked with the period of measurements. By considering a complete year of measurements, in the case of the Klobuchar model, there is a compensation of the residual error and so it gives virtually good results. By considering a shorter period, the NeQuick model seems to produce better results. But this effect should be investigated further by considering a quarter of year as a period of simulation and by using a shorter sampling period in order to have a representative statistics.

Nevertheless, these results show also that there is no significant improvement in comparison with the Klobuchar model. The ionospheric error remains in almost all configurations the dominant one for single frequency absolute positioning receivers. Without using a dual frequency receiver or a satellite based augmentation system or even a ground based augmentation systems, this error source will still remain the major source of inaccuracy.

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