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NeQuick2 model for single-frequency ionospheric delay mitigation

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Abstract: The ionospheric delay is the major current source of potential range delay for single-frequency GNSS users. Single-frequency GNSS users are in utmost need of an ionospheric model to eliminate the ionospheric delay to a high degree of accuracy. GPS system uses the Klobuchar model for this task, which its coefficients are sent through the GPS navigation message to GPS users. Klobuchar model uses the Ionospheric Corrections Algorithm (ICA) designed to account for approximately 50% (rms) of the ionospheric range delay. The NeQuick is an ionospheric electron density model that has been adopted for single-frequency positioning applications in the frame work of the European Galileo project. A comparitive study between the behaviour of the GPS Single-frequency ionospheric modelling (Klobuchar model) and the Galileo proposed approach for this task (NeQuick model) is presented in this paper. The vertical range delay correction by the two models have been assessed using the highly accurate IGS-global ionospheric maps for three different latitude stations in Egypt. The study was carried out over three different months so that each of them reflects a different state of solar activity, which is a major indication for the ionospheric activity. From the study, it can be concluded that the behaviour of Klobuchar model is better than the NeQuick model for quiet and medium ionospheric activity states. However, for active ionospheric state NeQuick model gives a better behaviour than Klobuchar model for different latitude geographic regions.

Keywords: GPS, Galileo, NeQuick2 model, Ionospheric modelling

1. Introduction

Global Navigation Satellite System (GNSS) users face many error sources that affect the quality of GNSS operations. These errors have different sources namely, satellite dependent errors (satellite orbital error, satellite clock error and relativistic effects), receiver dependent errors (receiver clock error and antenna phase centre variations) and signal path dependent errors (ionospheric errors, tropospheric errors, cycle slips and multipath). The ionospheric error is the major source of error faced by single-frequency GNSS users. However, use of double–frequency GNSS measurements could eliminate the ionospheric error to a high degree of accuracy. The urgent need to eliminate the ionospheric error by single-frequency GNSS users creates the necessity of different options for different GNSS systems. GPS, the American GNSS system, uses the Klobuchar model (Klobuchar, 1982) to eliminate the ionospheric error to a certain degree of accuracy.

The development studies of Galileo, the future European GNSS system which assumes to offer better performance than GPS, proposes using NeQuick model to eliminate the ionospheric error for single-frequency operations (Radicella et al., 2003). The NeQuick (Hochegger et al., 2000; Radicella and Leitinger, 2001) is an ionospheric electron density model developed at the Aeronomy and Radio propagation Laboratory of The Abdus Salam International Centre for Theoretical Physics (ICTP), Trieste, Italy, and at the Institute for Geophysics, Astrophysics and Meteorology (IGAM) of the University of Graz, Austria in the framework of the European Commission COST action 251. Historically the NeQuick has to be considered as an evolution of the DGR profile proposed by (Di Giovanni and Radicella, 1990), and subsequently modified by (Radicella and Zhang, 1995). The first version of the model has been used by the European Space Agency (ESA) European Geostationary Navigation Overlay Service (EGNOS) project for assessment analysis and has been adopted for single-frequency positioning applications in the frame work of the European Galileo project. It has also been adopted by the International Telecommunication Union, Radio communication Sector (ITU-R) as a suitable method for total electron content (TEC) modeling (ITU, 2003).

This paper presents a comparitive study between the behaviour of the GPS ionospheric model (Klobuchar model) and the proposed Galileo ionospheric model (NeQuick model) with respect to the highly accurate IGS-Global Ionospheric Maps (GIM's) for three stations over a period of three months. The vertical range delay correction offered by both models was assessed using the range delay extracted using the

IGS-GIM's. The study involved different ionospheric activity states with respect to the solar activity (quiet, medium and active ionospheric activity states).

The paper starts with a short description of the Klobuchrar model and the NeQuick model. The comparison of the performance of the two models is presented in the subsequent section followed by discussion and finally the main conclusions are listed.

2. Klobuchar model

The Klobuchar model (Klobuchar, 1982), was designed based on the Bent model (Llewellyn and Bent, 1973). The model is built on a simple cosine representation of the ionospheric delay, with a fixed phase-zero at 14.00 hours local time and a constant night time offset of 5 nanoseconds. The period and amplitude of the ionospheric delay are represented as third degree polynomials in local time and geomagnetic latitude. The eight time-varying coefficients of the two polynomials are broadcast in the GPS navigation message and are updated daily. These coefficients are selected from 370 possible sets of constants by the GPS master control station and placed in the satellite upload message for downlink to the user. These coefficients are based on two parameters, day of the year and average solar 10.7-cm flux value (the solar flux density at 10.7cm wavelength) for the previous five days.

The model assumes an ideal smooth behaviour of the ionosphere, therefore any significant fluctuations from day to day will not be modelled properly. The accuracy of the model is limited to 50-60% of the total effect (Dodson, 1988). Under special circumstances, such as severe ionosphere activity at low elevations, the range error can be of order of 50 m (Newby et al., 1990).

This model has one main advantage, which is its simplicity and the low computation time but it also has many shortcomings:

- Low accuracy for computing the ionospheric delay correction (50-60%) (Dodson, 1988)
- The algorithm does not properly represent the behaviour of the ionosphere in the near-equatorial region of the world, where the highest values of the ionospheric delay occurre (Klobuchar, 1982).
- The algorithm is very poor in high latitude regions where the ionospheric variability is high due to auroral processes
- The model is unable to represent the behaviour of the ionosphere when the ionosphere differs by substantial amounts from its average behaviour.

3. NeQuick2 model

NeQuick2 (Nava et al., 2008) is the latest version of the NeQuick ionosphere electron density model (Hochegger et al., 2000; Radicella and Leitinger, 2001) developed at the Aeronomy and Radiopropagation Laboratory (now T/ICT4D Laboratory) (ICTP, 2015) of the Abdus Salam International Centre for Theoretical Physics (ICTP) - Trieste, Italy with the collaboration of the Institute for Geophysics, Astrophysics and Meteorology of the University of Graz, Austria.

The NeQuick is a quick-run ionospheric electron density model particularly designed for trans-ionospheric propagation applications. To describe the electron density of the ionosphere up to the peak of the F2 layer, the NeQuick uses a profile formulation which includes five semi-Epstein layers with modelled thickness parameters. Three profile anchor points are used: the E layer peak, the F1 peak and the F2 peak, that are modelled in terms of the ionosonde parameters foE, foF1, foF2 and M(3000)F2. These values can be modelled (e.g. ITU- R coefficients for foF2, M3000) or experimentally derived. A semi-Epstein layer represents the model topside with a height- dependent thickness parameter empirically determined.

The basic input parameters of the model are geographic coordinates, epoch, solar activity index and values of foF2 and M(3000)F2. Different options for the input or derivation of these two parameters could be used depending on the purpose. Amongst these options are, ITU-R coefficients, measured values, regional grid values maps, regional or global maps based on (effective ionisation level) Az derived from regional or global vertical TEC maps and global maps based on Az values calculated from slant TEC values measured from sets of ground stations. The last option is the proposed option for operational purposes in satellite navigation. The NeQuick model with the ITU-R ionospheric coefficients could be installed in a Galileo receiver such that the model would be driven using the Az parameter that is a function of the receiver location and satellite ray-path. The Az parameter would be determined from measured slant TEC data obtained during the previous 24 hours at monitoring stations distributed around the world. The Az parameter would be broadcast to the user in the navigation message and updated at least once a day (Radicella et al., 2003). The output of the model is the electron density in the ionosphere as a function of height, geographic coordinates and epoch in Universal Time or Local Time.

Several changes have been introduced in the version 1 of the NeQuick model. The most important modification is related to the bottom side formulation in terms of the modeling of the F1 layer peak electron density, height and thickness parameter. Concerning the model top side, a new formulation of the shape parameter k has been adopted. All the model improvements have therefore been considered to finalize a new version of the model: the NeQuick2 (Nava et al., 2008).

4. Behaviour test study

The objective of the study is to compare the behaviour of the Klobuchar and NeQuick models with respect to the IGS-GIM's under different ionospheric activity circumstances. For this purpose, three different latitude stations have been chosen to reflect different latitude regions in Egypt (see Table 1). The study compared the range delay corrections offered by the two models with respect to the IGS-GIM's for (GPS-L1 frequency and Galileo-E2L1E1) (1575.42 MHz) over three different months (Table 2), each month reflects a different state of solar activity based upon Sun Spot Number (SSN) which is a major indicator of ionospheric activity state (quiet, medium and active ionospheric activity states) (SIDC, 2016).The tested periods are free from disturbed ionospheric conditions as Kp-index (WDC, 2007) shows (Table 2), so the GNSS corrections are expected to be reliable.

Table 1: The geographical positions of the test stations

Station ID	Latitude degree	Longitude degree	Height meters
ASWAN	24.088 N	32.899 E	79.000
Asyut	27.183 N	31.182 E	37.000
Alexandria	31.200 N	29.900 E	0.000

Table 2: The dates, activity states, average Sun Spot Number and Kp-index of the tested periods

Activity state	Quiet	Medium	Active
Month	February 1998	April 1999	September 2001
Average Sun Spot no.	40	64	151
Kp-index	2	3	3

4.1 Lower latitude geographic region

The study's findings for ASWAN station, which represents the near-equatorial region, can be characterized with the highest values of the peak-electron density with the most pronounced amplitude and phase scintillation effects. These are shown in Figures 1, 2 and 3. These figures show the vertical range delay correction offered by the Klobuchar model, NeQuick model and highly accurate IGS-GIM's. The vertical range delay differences between both models and the IGS-GIM's are shown in Figures 4, 5 and 6.

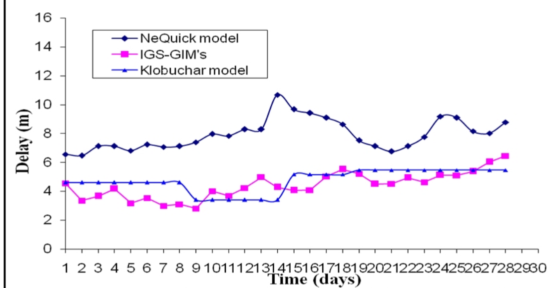

Figure 1: L1 range delay correction (ASWAN station) (Februray,1998)

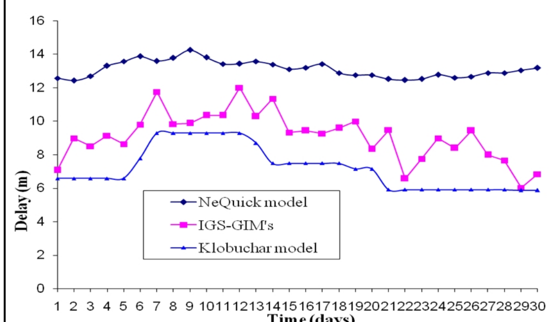

Figure 2: L1 range delay correction (ASWAN station) (April,1999)

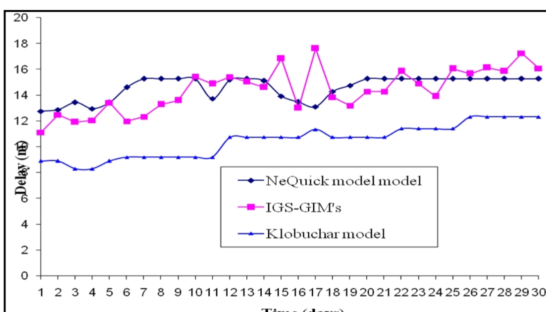

Figure 3: L1 range delay correction (ASWAN station)(September,2001)

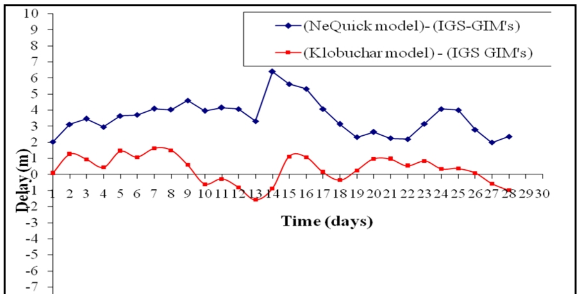

Figure 4: L1 range delay difference (ASWAN station) (Februray,1998)

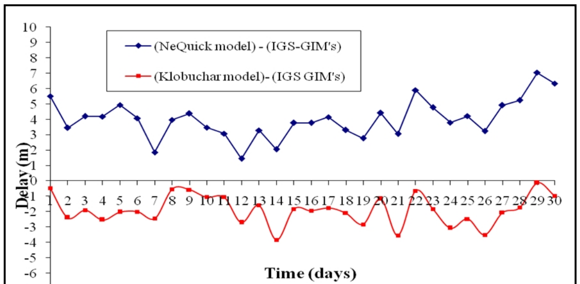

Figure 5: L1 range delay difference (ASWAN station) (April,1999)

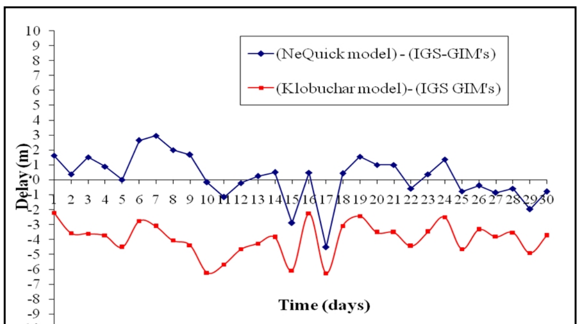

Figure 6: L1 range delay difference (ASWAN station)(September,2001)

4.2 Middle latitude geographic region

The study's findings for Asyut station, which represent the middle-latitude region in Egypt, are shown in Figures 7, 8 and 9. These figures show the vertical range delay correction offered by the Klobuchar model, NeQuick model and the highly accurate IGS-GIM's. The vertical range delay differences between both models and the IGS-GIM's are shown in Figures 10, 11 and 12.

4.3 High latitude geographic region

The study's findings for Alexandria station, which represent the high-latitude region in Egypt, are shown in Figures 13, 14 and 15. These Figures show the vertical range delay correction offered by the Klobuchar model, NeQuick model and the highly accurate IGS-GIM's. The vertical range delay differences between both models and the IGS-GIM's are shown in Figures 16, 17 and 18.

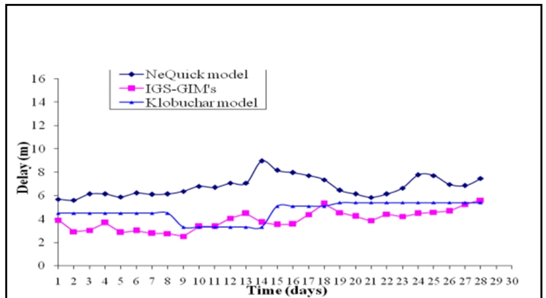

Figure 7: L1 range delay correction (ASYUT station) (Februray,1998)

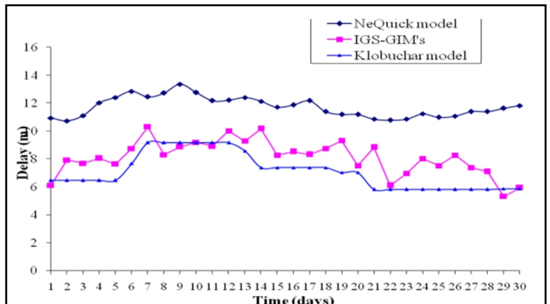

Figure 8: L1 range delay correction (ASYUT station) (April,1999)

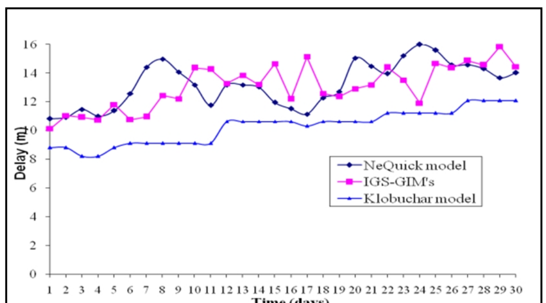

Figure 9: L1 range delay correction (ASYUT station)(September,2001)

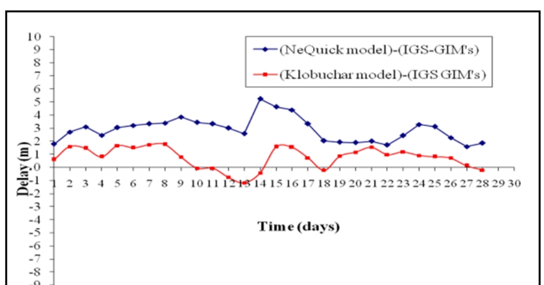

Figure 10: L1 range delay difference (ASYUT station) (Februray,1998)

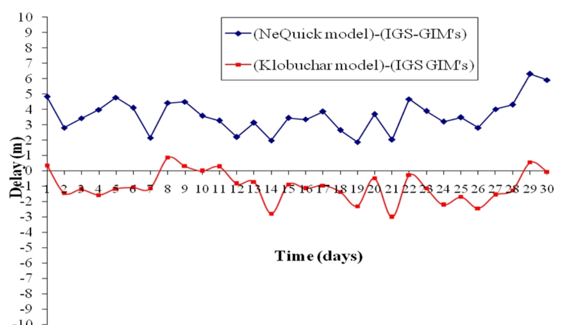

Figure 11: L1 range delay difference (ASYUT station) (April,1999)

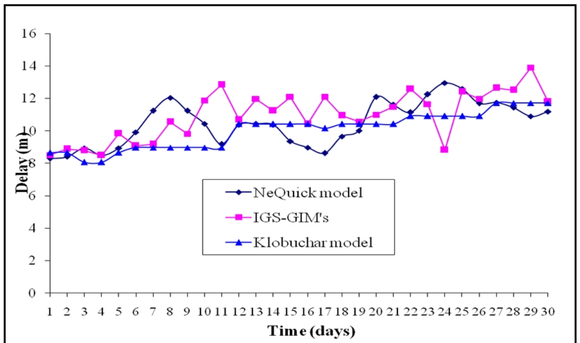

Figure 15: L1 range delay correction (ALEXANDRIA station)(September,2001)

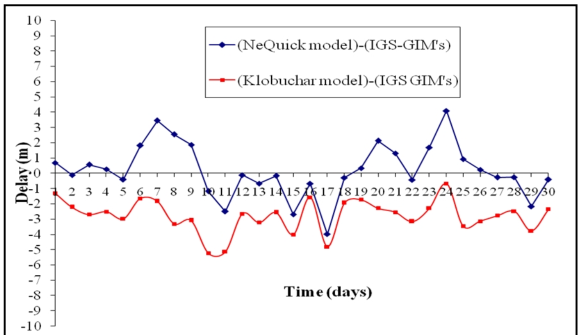

Figure 12: L1 range delay difference (ASYUT station)(September,2001)

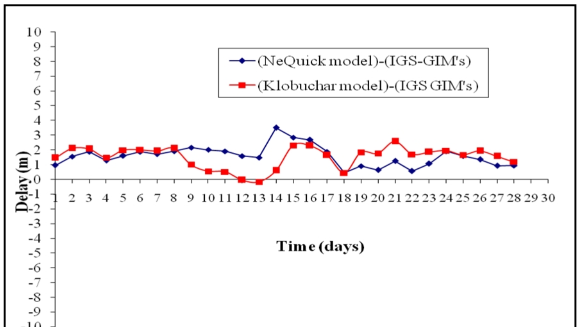

Figure 16: L1 range delay difference (ALEXANDRIA station) (Februray,1998)

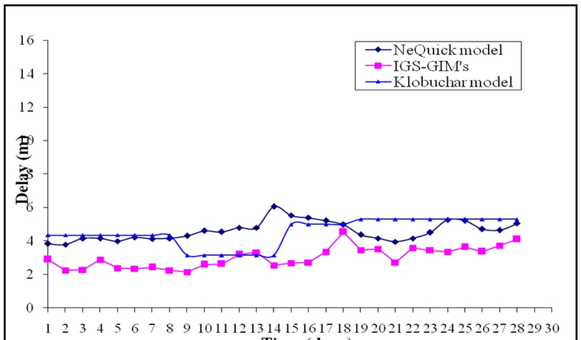

Figure 13: L1 range delay correction (ALEXANDRIA station) (Februray,1998)

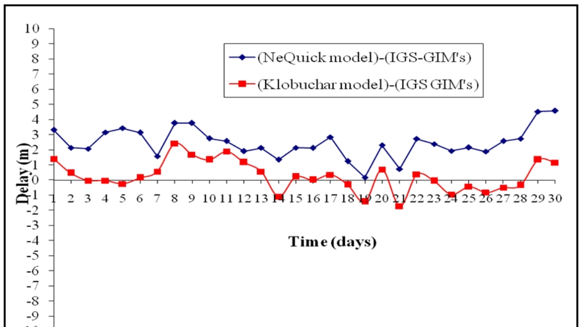

Figure 17: L1 range delay difference (ALEXANDRIA station) (April,1999)

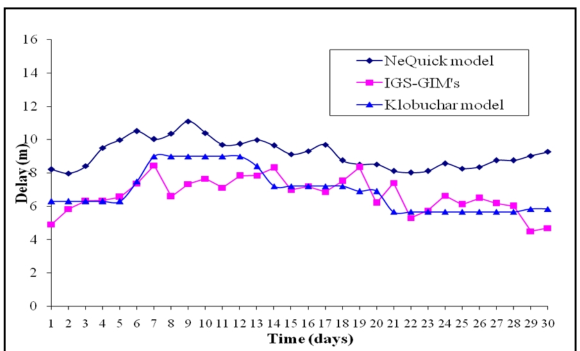

Figure 14: L1 range delay correction (ALEXANDRIA station) (April,1999)

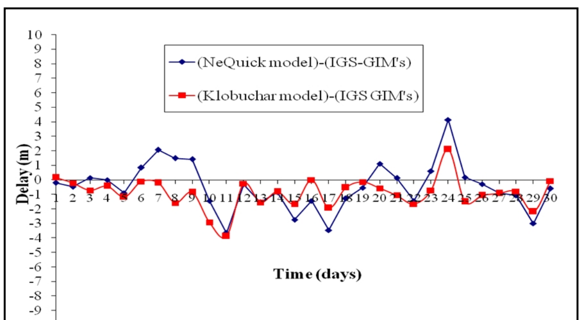

Figure 18: L1 range delay difference (ALEXANDRIA station)(September,2001)

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The arithmetic average for L1 vertical range delay difference (in meters) for the two models from IGS-estimates for the different geographical regions as well as different ionospheric activity states (tested time periods) are shown in table 3. The RMS (meters) of the L1 vertical range delay differences for the different geographical regions as well as different ionospheric activity states (tested time periods) are shown in table 4.

The average L1 vertical delay difference
= [Σ delay differences / no. of days in a month] --------- (1)

The RMS of L1 vertical delay differences

$$= \sqrt{\frac{\sum_{i=1}^{n}(X-\mu)^2}{n-1}} \quad \text{--------- (2)}$$

where X = vertical range delay difference,
μ= the average of vertical delay differences
n = number of days in a month

5. Discussion

It can be seen from Figures 1, 2 and 3 that for lower-latitude geographic region (Aswan station), the Klobuchar model is offering better behaviour than the NeQuick model as it provides range corrections more closely to the IGS-GIM's corrections for quiet and medium ionospheric states of activity however for active ionospheric state, NeQuick model is offering better behavior than Klobuchar model. NeQuick model is able to show day-to-day variations in the range delay corrections due to its dependence on daily values of average sun spot number while Klobuchar model is unable to show day-to-day variations as the ionospheric coefficients sent in the GPS navigation message is not updated on daily basis. It can be seen that the Klobuchar model-ionospheric coefficients sent in the GPS navigation message were updated four times during February 1998 (quiet ionospheric state), eight times during April 1999 (medium ionospheric state) and fourteen times during September 2001 (active ionospheric state). It can be concluded from Table 3 that for near equatorial latitude geographic region, the behaviour of Klobuchar model is better than the NeQuick model by 90% (average difference) for quiet ionospheirc activity state. For medium ionospheric activity state, the behaviour of Klobuchar model is better than the NeQuick model by 52% (average difference). While for the active ionospheric state, the behaviour of NeQuick model is better than the Klobuchar model by 94% (average difference).

Table 3: The average (metres) for L1 vertical range delay difference from IGS estimates for different-latitude geographic regions

Time	Ionospheric Activity State	Lower-latitude region ASWAN Station		Middle-latitude region Asyut station		High-latitude region Alexandria station	
		Klobuchar model	NeQuick model	Klobuchar model	NeQuick model	Klobuchar model	NeQuick model
Feb-1998	Quiet	0.339	3.548	0.755	2.897	1.513	1.588
Apr-1999	Medium	-1.899	4.014	-1.016	3.615	0.256	2.469
Sep-2001	Active	-3.946	0.193	-2.781	0.184	-0.914	-0.472

Table 4: The RMS (metres) for L1 vertical range delay difference for different latitude geographic regions

Time	Ionospheric Activity State	Lower-latitude region ASWAN Station		Middle-latitude region Asyut station		High-latitude region Alexandria station	
		Klobuchar model	NeQuick model	Klobuchar model	NeQuick model	Klobuchar model	NeQuick model
Feb-1998	Quiet	0.843	1.095	0.815	0.924	0.727	0.697
Apr-1999	Medium	0.959	1.252	0.981	1.087	0.994	0.993
Sep-2001	Active	1.171	1.57	1.064	1.75	1.066	1.643

It can be concluded from Figures 7, 8 and 9 that for middle-latitude geographic region (Asyut station), the Klobuchar model is offering better behaviour than the NeQuick model as it provides range corrections more closely to the IGS-GIM's corrections except for active ionospheric activity state. NeQuick model is able to show day-to-day variations in the range delay corrections while Klobuchar model is unable to show day-to-day variations. It can be concluded from Table 3 that for middle-latitude geographic region, the behaviour of Klobuchar model is better than the NeQuick model by 73% (average difference) for quiet ionospheirc activity state. For medium ionospheric activity state, the behaviour of Klobuchar model is better than the NeQuick model by 72% (average difference). However, for the active ionospheric state, the behaviour of NeQuick model is better than the Klobuchar model by 93% (average difference).

It can be concluded from Figures 13, 14 and 15 that for high latitude geographic region (Alexandria station), the two models are offering similar behaviour during all states of ionospheric activity. It can be concluded from Table 3 that for high-latitude geographic region, the behaviour of the two models is similar for quiet ionospheirc activity state. For medium ionospheric activity state, the behaviour of Klobuchar model is better than the NeQuick model by 93% (average difference). Also for the active ionospheric state, the behaviour of NeQuick model is better than the Klobuchar model by 48% (average difference).

Generally, Klobuchar model offers better behaviour in correcting range delay comparing with NeQuick model in different geographic regions for quiet and medium states of ionospheric activity where the ionosphere is less variable and the TEC values are not at maximum values. However, NeQuick model offers better behaviour comparing with Klobuchar model for different geographic region in active state of the ionosphere where the ionosphere's variability is high and the TEC values at maximum.

6. Conclusions

It can be concluded that for different latitude geographic regions, the behaviour of Klobuchar model is better than the NeQuick model for quiet and medium ionospheric activity states. However, for active ionospheric state NeQuick model gives a better behaviour than Klobuchar model for different latitude geographic regions. These findings could be justified based to two facts. First, Klobuchar model assumes an ideal smooth behaviour of the ionosphere, therefore it performs better in none-active state of the ionosphere (quiet and medium ionospheric states of activity). Secondly, the accuracy of NeQuick model depends on (effective ionisation level) Az derived from regional or global vertical TEC maps and global maps based on Az values calculated from slant TEC values measured from sets of ground stations. The lack of permanent ground stations in the study area (Egypt) affects the accuracy of ionisation level and consequently the overall accuracy of the model.

NeQuick model is able to show day-to-day variations in the range delay corrections due to its dependence on daily values of average sun spot number while Klobuchar model is unable to show day-to-day variations due to the limitations in the GPS navigation message - ionospheric coefficients updating.

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