ARTIFICIAL SATELLITES, Vol. 53, No. 4 – 2018
DOI: 10.2478/arsa-2018-0010

NEQUICK2 MODEL BEHAVIOUR FOR GLOBAL IONOSPHERIC DELAY MITIGATION DURING SOLAR CYCLE-24

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ABSTRACT: The ionospheric delay is the major current source of potential range delay for single-frequency GNSS users. Different ionospheric delay mitigation methods have been developed to mitigate the ionospheric delay effects for single-frequency users. The NeQuick is a quick-run ionospheric electron density model particularly designed for trans-ionospheric propagation applications developed at the Aeronomy and Radio propagation Laboratory of the Abdus Salam International Centre for Theoretical Physics (ICTP), Italy. NeQuick2 is the latest version of the NeQuick ionosphere electron density model. NeQuick model 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 satellite navigation system (Galileo). NeQuick2 model adopted modifications related to the modeling of the F1 layer peak electron density, height and thickness parameter. Also, a new formulation of the shape parameter k has been adopted. This paper presents a global study for the behavior of the modified NeQuick2 model. The zenith ionospheric range delay correction by the model has been assessed using the highly accurate IGS-Global Ionospheric Maps (IGS-GIMs) for two different-latitude stations (Aswan, Egypt) (low–latitude) (24.1^{o} N) and (Helsinki, Finland) (high-latitude) (60.2^{o} N). The study was carried out during current solar cycle-24 over three different months that each of them reflects a different state of solar activity. It can be concluded that NeQuick2 model globally presents overestimation for ionospheric delay for quiet and medium ionospheric activity states respectively, while the model presents underestimation for high activity state of the ionosphere layer.

Key Words 1. NeQuick2 model 2. Single frequency 3. Ionospheric delay mitigation 4. Solar cycle-24

1. INTRODUCTION

Quality of GNSS observations is affected by different sources of errors. The main error types are; 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 major source of error that affects GNSS observations is the ionospheric delay (Kunches and Klobuchar, 2001), however using dual–frequency GNSS observations could eliminate the ionospheric delay to a high degree of accuracy. Single-frequency GNSS users adopt different options for ionospheric delay mitigation. GPS, the American GNSS system uses the Klobuchar model (Klobuchar, 1982) to eliminate the ionospheric error to a certain degree of accuracy (50 – 60%).

NeQuick model was used to eliminate the ionospheric error for single-frequency operations in the development studies of Galileo, the future European GNSS system (Radicella et al., 2003). The NeQuick model is an ionospheric electron density model developed in the framework of the European Commission COST action 251 (Hochegger et al., 2000; Radicella and Leitinger, 2001). The NeQuick has to be considered as an evolution of the DGR profile proposed by (Di Giovanni and Radicella, 1990), and 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. It has also been adopted by the International Telecommunication Union, Radio communication Sector (ITU-R) for modeling the total electron content (TEC) (ITU, 2003).

This paper presents an assessment study for the global behaviour of the Nequick2 model with respect to the highly accurate IGS-GIMs for two different latitude stations over a period of three months during current solar cycle-24. Each month reflects different ionospheric activity states (quiet, medium and active). The zenith range delay correction offered by the model was assessed using the range delay extracted from the IGS-GIMs.

2. NEQUICK2 MODEL

NeQuick 2 (Nava et al., 2008) is the latest version of the NeQuick ionosphere electron density model (Hochegger et al., 2000; Radicella and Leitinger, 2001) developed in the framework of the European Commission COST action 251 at the Aeronomy and Radio propagation Laboratory (ICTP, 2017) 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 (Radicella et al., 2003) is a quick-run ionospheric electron density model particularly designed for trans-ionospheric propagation applications. The NeQuick uses a profile formulation which includes five semi-Epstein layers with modelled thickness parameters to describe the electron density of the ionosphere up to the peak of the F2 layer. 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 through (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 (Nava et al., 2008).

The NeQuick model's input parameters are; geographic coordinates, epoch, solar activity index and values of foF2 and M(3000)F2. (foF2 and M(3000)F2) parameters could be derived through different options. These options involved; (ITU-R) coefficients, measured values and regional grid values maps. Those parameters could be derived also for satellite navigation operations through 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 NeQuick model with the ITU-R ionospheric coefficients could be installed in a Galileo receiver (Radicella et al., 2003) 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 broadcasted to the user in the navigation message and updated at least once a day (Radicella et al., 2003). The electron density in the ionosphere is the output of the model as a function of height, geographic coordinates and epoch in Universal Time or Local Time. NeQuick2 model adopted several changes in the first version of the model (Nava et al., 2008). The modifications are related to the bottomside formulation in terms of the modeling of the F1 layer peak electron density, height and thickness parameter. The model's topside adopted a new formulation of the shape parameter k. A number of recent studies investigated the behavior of the NeQuick2 model such as Ezquer et al. (2018), Okoh et al. (2018) and Perna et al. (2018).

Ezquer et al. (2018) analyzed the capability of the NeQuick 2 and IRI Plas models to predict VTEC over the low latitude and South American sector using vertical total electron content (VTEC) measurements obtained from GPS satellite signals. They concluded that performance of IRI Plas model for low latitude stations is better than that of NeQuick2 model and performance of NeQuick2 model is better than that of IRI Plas model for highest latitudes.

Okoh et al. (2018) used GNSS observations from 36 globally distributed locations to evaluate performances of both NeQuick-2 and IRI-Plas 2017 models from January 2006 to July 2017, covering more than the 11-year period of a solar cycle. The NeQuick predictions were generally better than the IRI-Plas prediction. The IRI-Plas model predictions were improved during periods of increased solar activity at the low latitude stations. The NeQuick underestimates the TEC values during the high solar activity years and overestimates it during local daytime for low and moderate solar activity years.

Perna et al. (2018) concluded that IRI-2012 and NeQuick2 bottom side profiles show significant deviations from ionosonde observations for two stations at the southern crest of the Equatorial Ionization Anomaly.

3. BEHAVIOUR TEST STUDY

The paper presents an assessment study for the global behavior of NeQuick2 model with respect to the IGS-GIMs (IGS, 2018b) whose accuracy is (2-8 TECU) (IGS, 2018a) under different ionospheric-activity circumstances. The study involved two different-latitude stations (Table 1) to reflect different latitude geographical regions. The study compared the zenith range delay corrections offered by the model with respect to the IGS-GIMs for (GPS-L1 frequency and Galileo-E2L1E1) (1575.42 MHz) over three different months during current solar cycle-24 (Table 2). The study's three months were chosen to reflect three different states of solar activity (quiet, medium and active) based upon Sun Spot Number (SSN) which is a major indication of ionospheric activity states (SIDC, 2017). The tested periods are free from disturbed ionospheric conditions as Kp-index (WDC, 2017) shows (Table 2).

Table 1. The Geographical positions for the tested stations.

Station ID	**Latitude degree**	**Longitude degree**	**Height meters**
ASWAN (Egypt)	24.088 N	32.899 E	79.000
Helsinki (Finland)	60.192 N	24.946 E	17.000

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

Activity state	**Quiet**	**Medium**	**Active**
Month	December 2008	March 2011	March 2014
Average Sun Spot no.	1.032	78.645	128.742
Kp-index	1	2	2

3.1 LOWER-LATITUDE GEOGRAPHIC REGION

(ASWAN) station represents the lower-latitude geographic regions which characterized with the highest values of the peak-electron density. Figures (1 to 3) show the zenith range delay correction from NeQuick2 model and IGS-GIMs as a reference. The zenith range delay differences between the model and the IGS-GIMs are shown in Figures 4, 5 and 6.

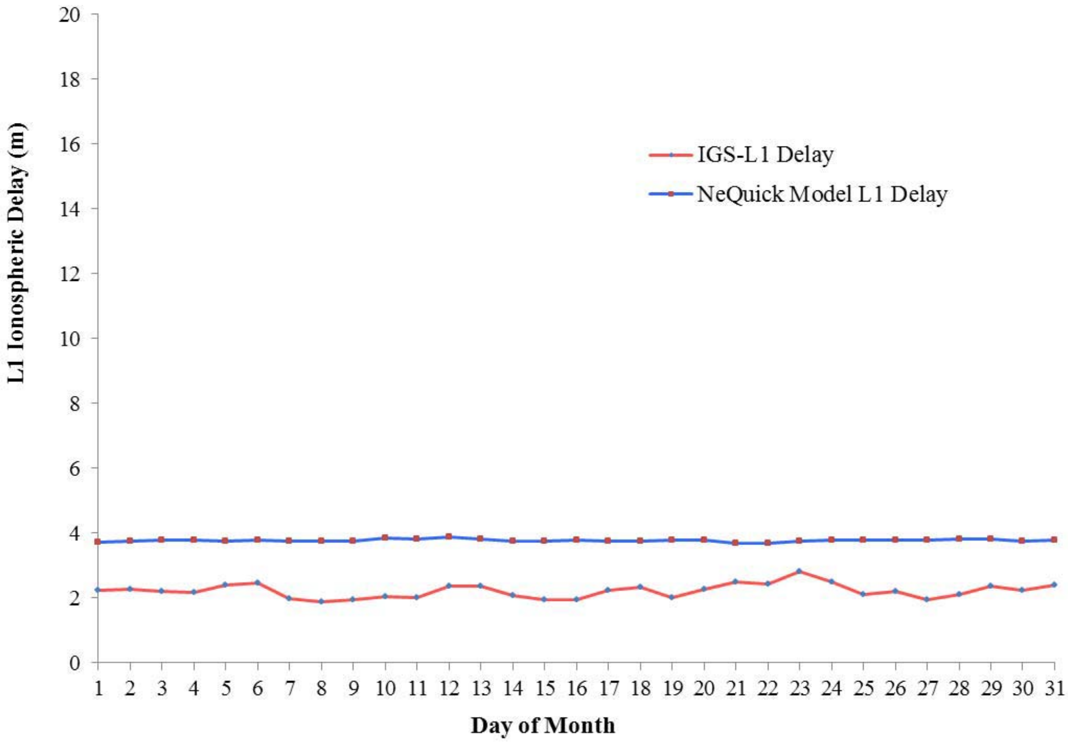

Fig. (1) : L1 Ionospheric Delay using NeQuick Model and IGS GIMs for Aswan Station during December 2008 (Low Ionosphere Activity State).

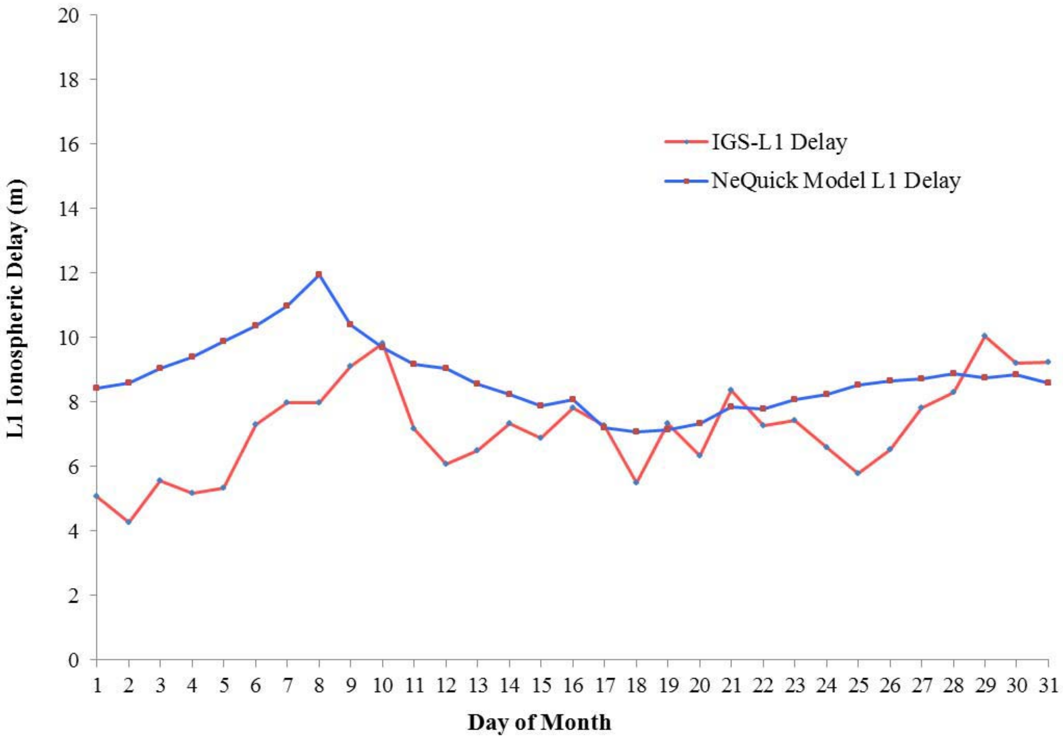

Fig. (2) : L1 Ionospheric Delay using NeQuick Model and IGS GIMs for Aswan Station during March 2011 (Medium Ionosphere Activity State).

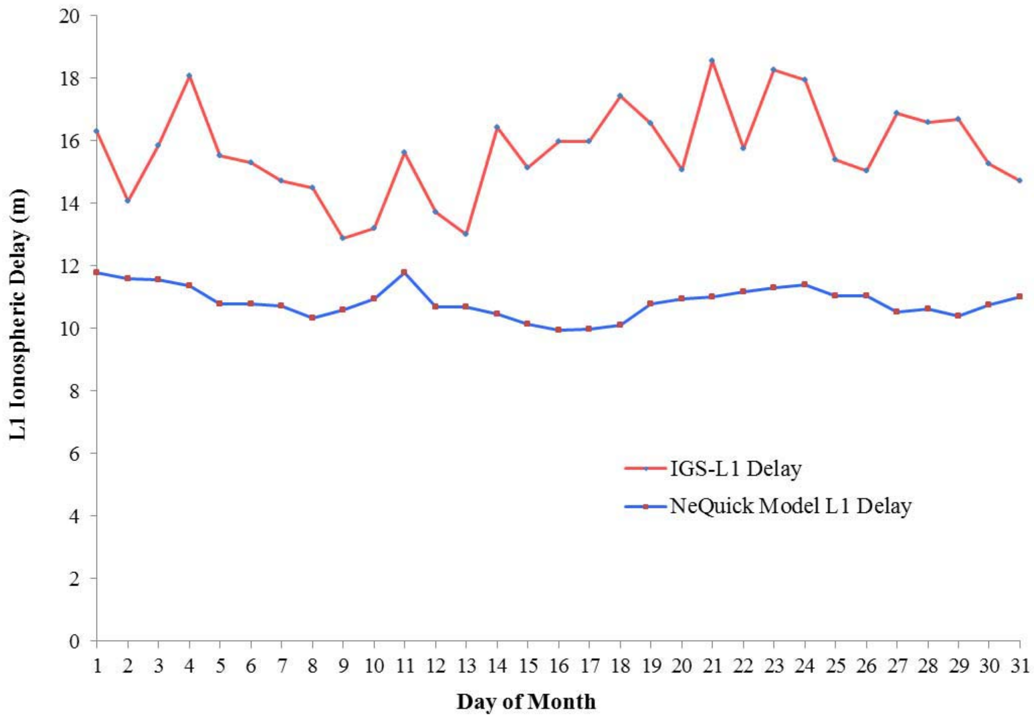

Fig. (3) : L1 Ionospheric Delay using NeQuick Model and IGS GIMs for Aswan Station during March 2014 (High Ionosphere Activity State).

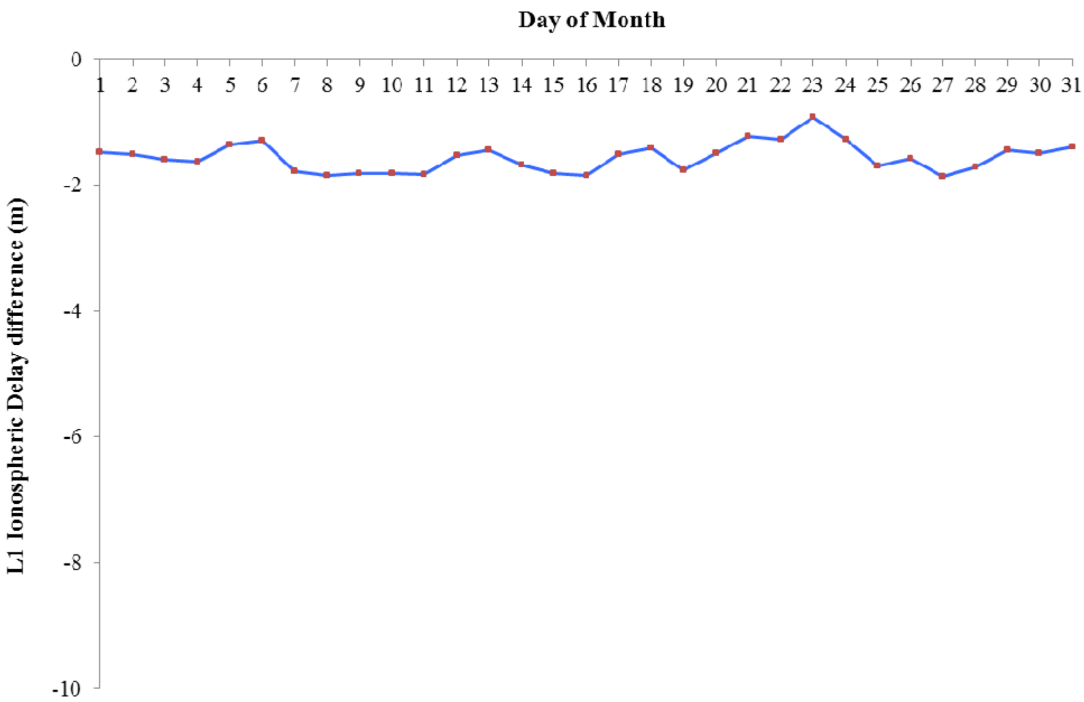

Fig. (4) : L1 Ionospheric Delay Difference (IGS GIMs- NeQuick model) for Aswan Station during December 2008 (Low Ionosphere Activity State).

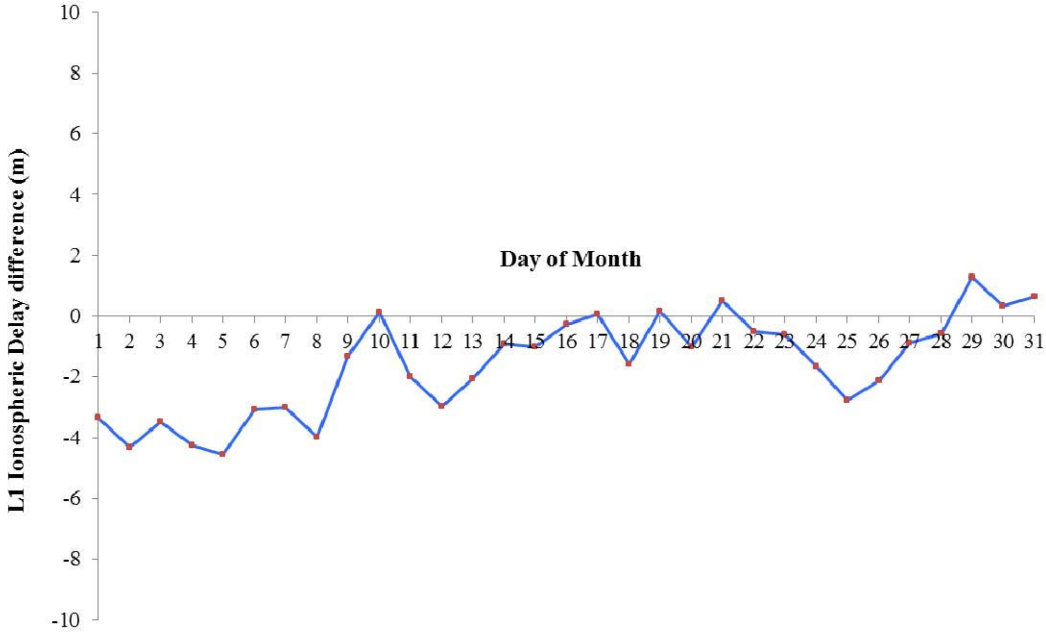

Fig. (5) : L1 Ionospheric Delay Difference (IGS GIMs- NeQuick model) for Aswan Station during March 2011 (Medium Ionosphere Activity State).

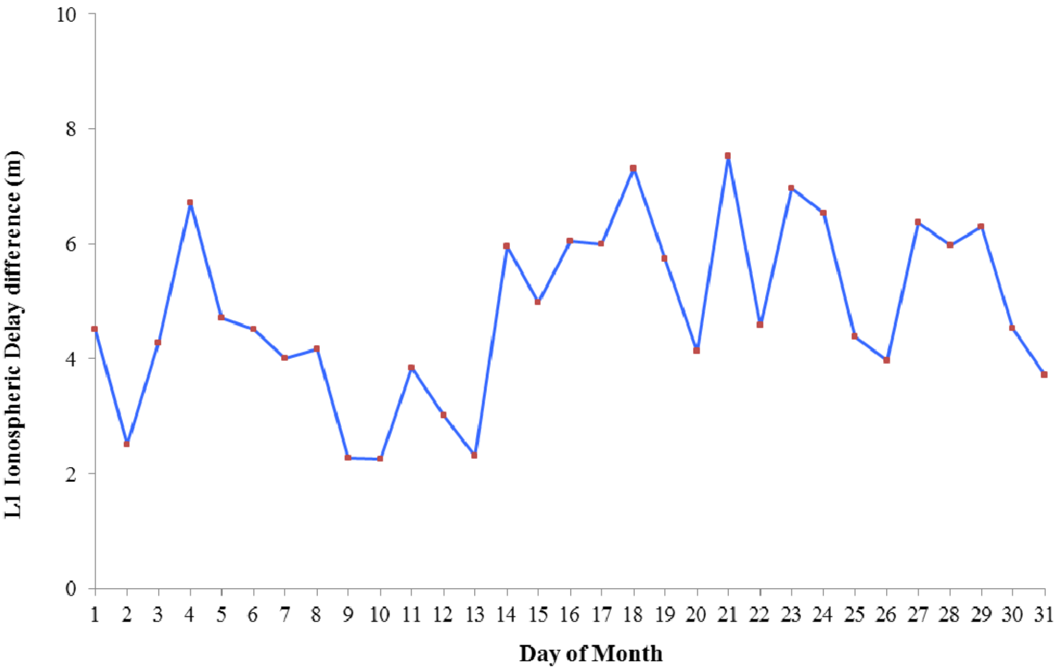

Fig. (6) : L1 Ionospheric Delay Difference (IGS GIMs- NeQuick model) for Aswan Station during March 2014 (High Ionosphere Activity State).

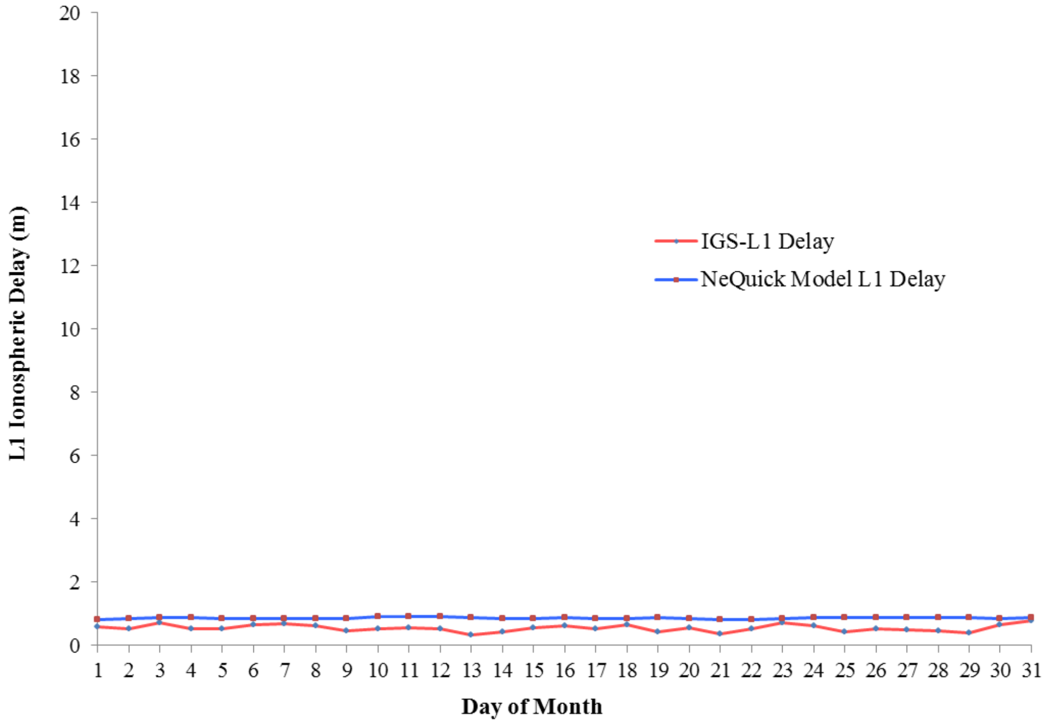

Fig. (7) : L1 Ionospheric Delay using NeQuick Model and IGS GIMs for Helsinki Station during December 2008 (Low Ionosphere Activity State).

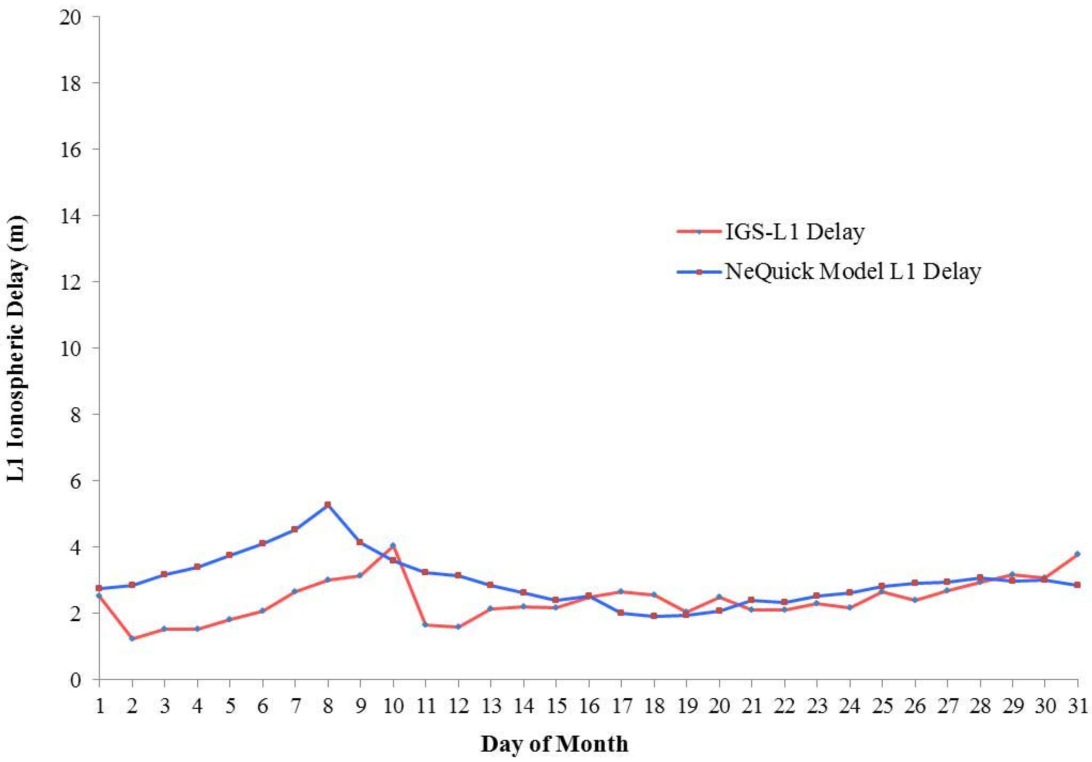

Fig. (8) : L1 Ionospheric Delay using NeQuick Model and IGS GIMs for Helsinki Station during March 2011 (Medium Ionosphere Activity State).

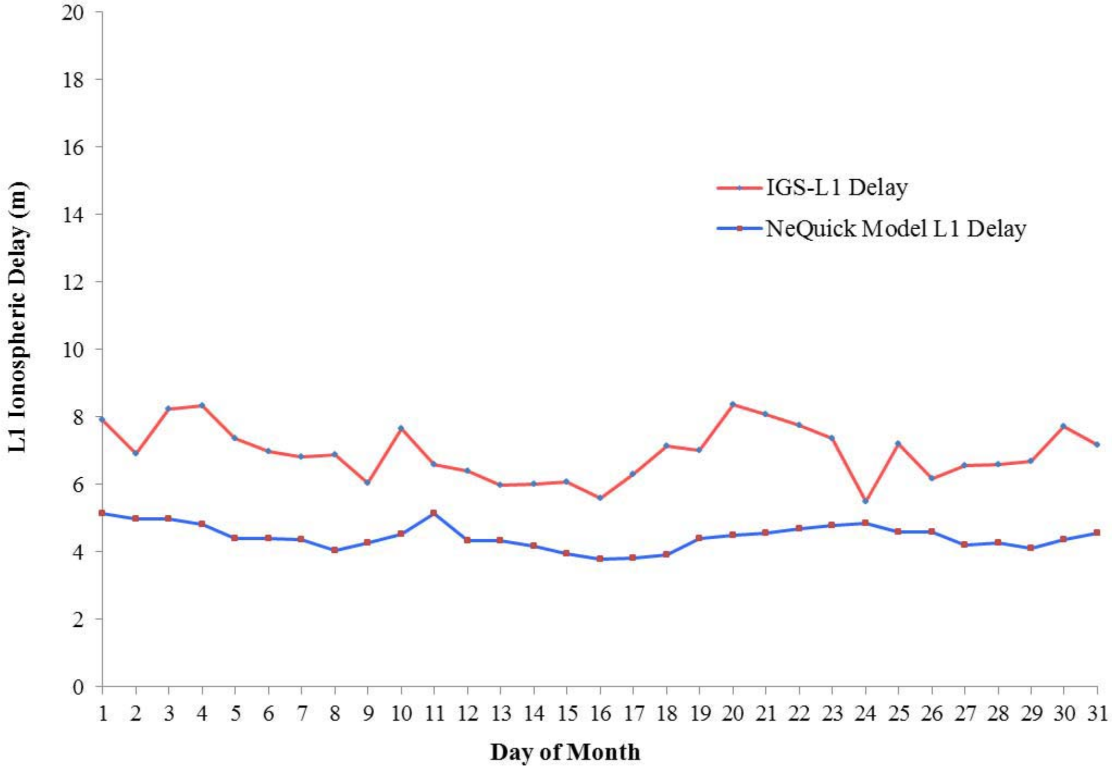

Fig. (9) : L1 Ionospheric Delay using NeQuick Model and IGS GIMs for Helsinki Station during March 2014 (High Ionosphere Activity State).

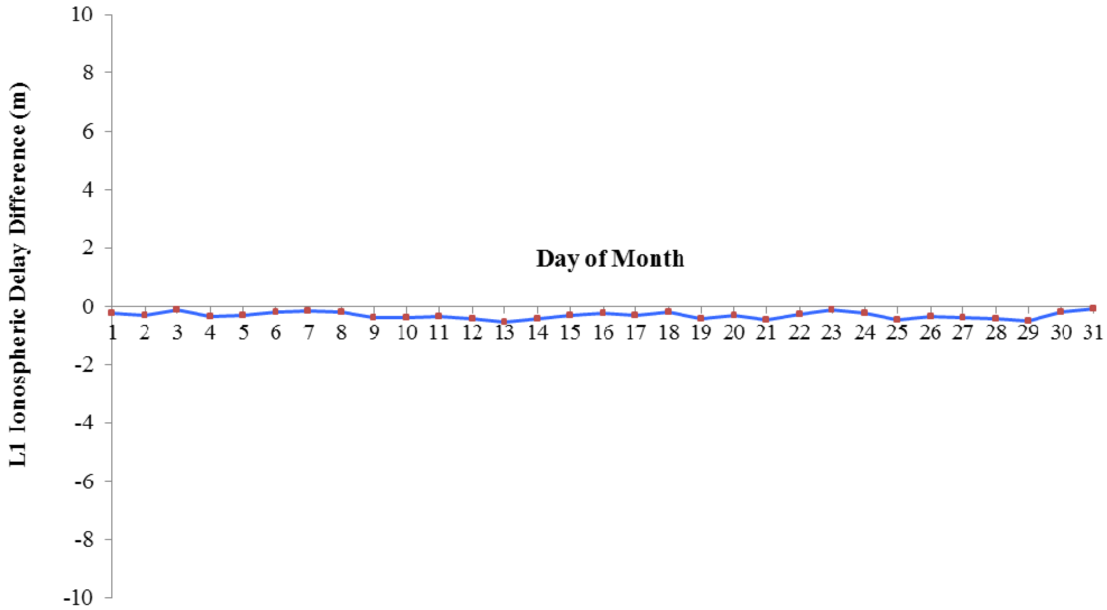

Fig. (10) : L1 Ionospheric Delay Difference (IGS GIMs- NeQuick model) for Helsinki Station during December 2008 (Low Ionosphere Activity State).

3.2 HIGH-LATITUDE GEOGRAPHIC REGION

(Helsinki) station represents the high-latitude geographic regions. Figures 7 to 9 show the zenith range delay correction from NeQuick2 model and IGS-GIMs as a reference. The zenith range delay differences between the model and the IGS-GIMs are shown in Figures 10, 11 and 12.

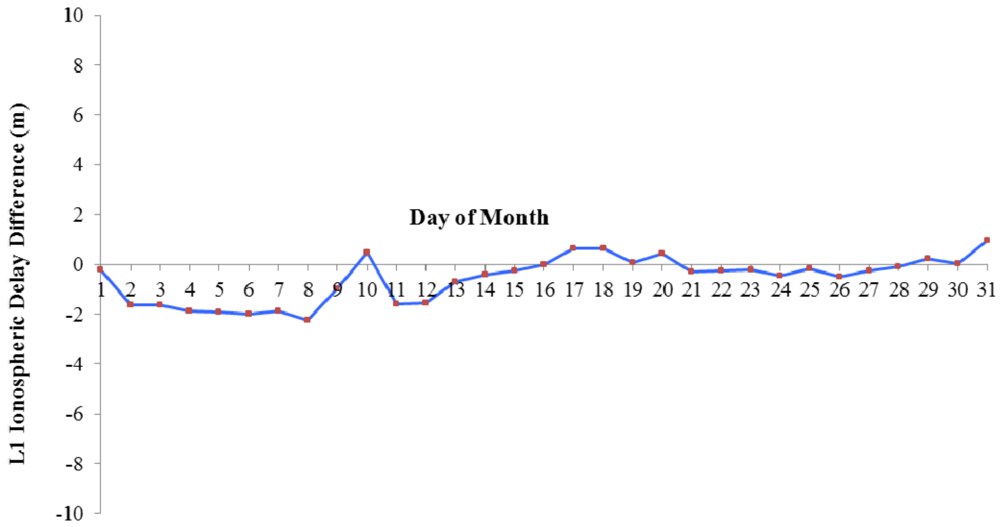

Fig. (11) : L1 Ionospheric Delay Difference (IGS GIMs- NeQuick model) for Helsinki Station during March 2011 (Medium Ionosphere Activity State).

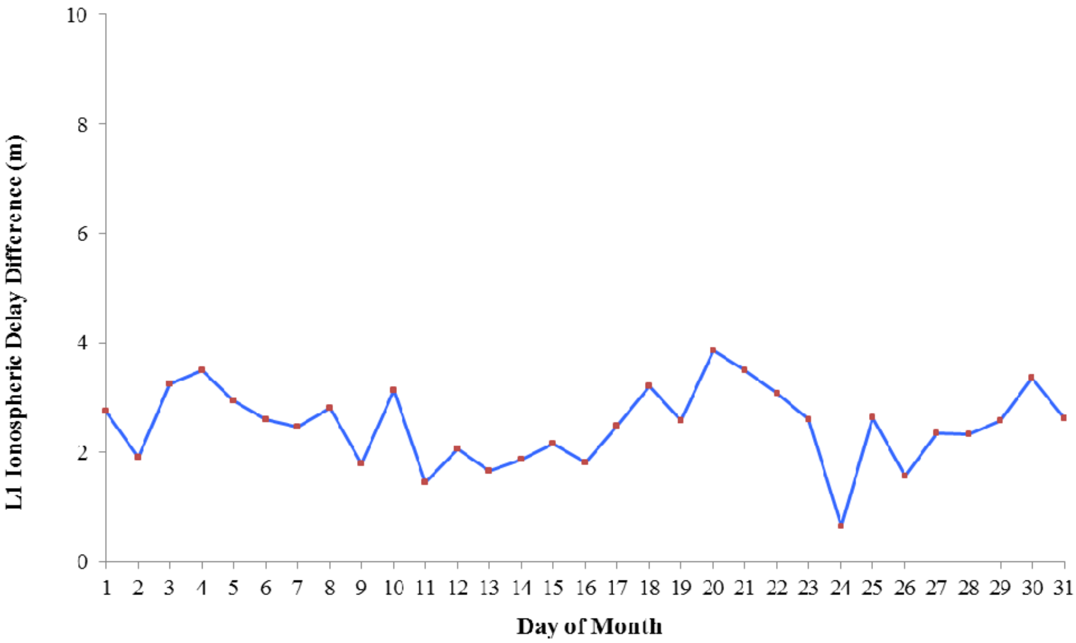

Fig. (12) : L1 Ionospheric Delay Difference (IGS GIMs- NeQuick model) for Helsinki Station during March 2014 (High Ionosphere Activity State).

Statistical analysis for L1 Ionospheric delay estimates from IGS GIMs & NeQuick2 model for Aswan and Helsinki stations are shown in tables 3& 4 respectively. Statistical analysis for L1 Ionospheric delay difference (IGS GIMs – NeQuick model) for Aswan and Helsinki stations are shown in tables 5& 6 respectively.

Table 3. Statistical analysis for L1 Ionospheric delay estimates (IGS GIMs & NeQuick2 model) for Aswan station (low-latitude).

	Low Ionosphere activity (December 2008)		**Medium Ionosphere activity (March 2011)**		**High Ionosphere activity (March 2014)**	
	IGS	**NeQuick2**	**IGS**	**NeQuick2**	**IGS**	**NeQuick 2**
Maximum (m)	2.833	3.874	10.051	11.933	18.543	11.793
Minimum (m)	1.892	3.702	4.270	7.078	12.868	9.945
Average (m)	2.218	3.777	7.174	8.756	15.693	10.848
Standard deviation (m)	0.217	0.039	1.450	1.115	1.489	0.495

Table 4. Statistical analysis for L1 Ionospheric delay estimates (IGS GIMs & NeQuick2 model) for Helsinki station (high-latitude).

	Low Ionosphere activity (December 2008)		**Medium Ionosphere activity (March 2011)**		**High Ionosphere activity (March 2014)**	
	IGS	**NeQuick2**	**IGS**	**NeQuick2**	**IGS**	**NeQuick2**
Maximum (m)	0.779	0.926	4.059	5.261	8.362	5.157
Minimum (m)	0.341	0.822	1.234	1.922	5.504	3.785
Average (m)	0.554	0.867	2.418	2.994	6.950	4.450
Standard deviation (m)	0.108	0.023	0.641	0.759	0.796	0.367

Table 5.: Statistical analysis for L1 Ionospheric delay difference (IGS GIMs – NeQuick2 model) for Aswan station (low-latitude).

	Low Ionosphere activity	**Medium Ionosphere activity**	**High Ionosphere activity**
	December 2008	**March 2011**	**March 2014**
Maximum (m)	-0.916	1.291	7.526
Minimum (m)	-1.859	-4.556	2.247
Range (m)	0.943	5.847	5.279
Average (m)	-1.559	-1.582	4.845
Standard deviation(m)	0.229	1.638	1.517

Table 6.:Statistical analysis for L1 Ionospheric delay difference (IGS GIMs – NeQuick2 model) for Helsinki station (high-latitude).

	Low Ionosphere activity	**Medium Ionosphere activity**	**High Ionosphere activity**
	December 2008	**March 2011**	**March 2014**
Maximum (m)	-0.093	0.943	3.851
Minimum (m)	-0.544	-2.257	0.643
Range (m)	0.451	3.200	3.208
Average (m)	-0.312	-0.577	2.499
Standard deviation(m)	0.113	0.905	0.707

4. DISCUSSION

The study's findings from Figures 1, 2 and 3 suggests that for lower-latitude geographic region (Aswan station), the NeQuick2 model is offering ionospheric delay values larger than IGS estimates for quiet and medium ionospheric activity states while the model's estimates is smaller than IGS estimates for high ionospheric activity state. IGS estimates offer higher fluctuations while the model offers smooth fluctuations for ionospheric delay. The model's estimates are following closely the IGS estimates for quiet activity state rather than both medium and high activity states. The range for the model estimates differences with respect to IGS estimates is 0.94m for quiet activity state while the range is 5.85m and 5.28 m for medium and high activity states. The average for the model estimates differences with respect to IGS estimates is 1.57m for quiet and medium activity states while the average is 4.85m for high activity states.

The study's findings from Figures 7, 8 and 9 suggests that for high-latitude geographic region (Helsinki station), the NeQuick2 model is offering ionospheric delay values lager than IGS estimates for quiet and medium ionospheric activity states while the model's estimates is smaller than IGS estimates for high ionospheric activity state. IGS estimates offer higher fluctuations while the model offers smooth fluctuations for ionospheric delay. The model's estimates are following closely the IGS estimates for quiet activity state rather than both medium and high activity states. The range for the model estimates differences with respect to IGS estimates is 0.45m for quiet activity state while the range is 3.20m for medium and high activity states. The average for the model estimates differences with respect to IGS estimates is 0.31m, 0.58m for quiet and medium activity states while the average is 2.5m for high activity states.

Generally, the NeQuick2 model's behavior in estimating the ionospheric delay is better in quiet and medium ionospheric activity states rather than high activity state. The model is offering close behavior with IGS estimates in high latitude geographic regions rather than low latitude regions.

5. CONCLUSIONS

It can be concluded that for low latitude regions, NeQuick2 model presents overestimation for ionospheric delay with 70%, 22 % for quiet and medium ionospheric activity states respectively, while the model presents underestimation for ionospheric delay with 31% for high activity state of the ionosphere layer.

For high latitude regions, NeQuick2 model presents overestimation for ionospheric delay with 56%, 24 % for quiet and medium ionospheric activity states respectively, while the model presents underestimation for ionospheric delay with 36% for high activity state of the ionosphere layer. The underestimation behaviour of the model (for high activity state of the ionosphere layer) could be due to the lack of a proper plasmaspheric model in its topside representation (Ezquer et al., 2018).

NeQuick model depends on daily solar radio flux (NOAA-NGDC, 2017), so it is able to show day-to-day variations in the range ionospheric delay corrections. The findings of this study are in agreement with other recent studies (e.g., Ezquer et al. (2018) and Okoh et al. (2018)) where performance of NeQuick2 model is better for highest latitudes and worst for lowest latitudes. Also, the NeQuick2 underestimates the TEC values during the high solar activity years and overestimates it during local daytime for low and moderate solar activity years.

REFERENCES

Di Giovanni, G. and S. R. Radicella (1990). An Analytical model of the electron density profile in the ionosphere. Advanced Space Research, 10, No.11, 27-30.

Ezquer R.G., L.A. Scidá, Y. Migoya Orué, B. Nava, M.A. Cabrera, C. Brunini (2018) .NeQuick 2 and IRI Plas VTEC predictions for low latitude and South American sector. Advances in Space Research, Volume 61, Issue 7, Pages 1803-1818.

Hochegger, G., Nava, B., Radicella, S.M., Leitinger, R., (2000). A family of ionospheric models for different uses. Physics and Chemistry of the Earth, Part C: Solar, Terrestrial & Planetary Science 25 (4), 307–310.

ICTP (2017). The Abdus Salam International Centre for Theoretical Physics (ICTP) (http://t-ict4d.ictp.it/) Accessed (15/3/2017).

IGS (2018a). (2003-2004) IGS Annual Report. (ftp://ftp.igs.org/pub/resource/pubs/2003-2004_IGS_Annual_Report.pdf) (Accessed 15/1/2018).

IGS (2018b). IGS-GIMs (International GNSS Service-Global Ionospheric Maps (IONEX format)) (ftp://cddis.gsfc.nasa.gov/gps/products/ionex/) (Accessed 15/1/2018).

ITU (2003). (International Telecommunication Union) Ionospheric propagation data and prediction methods required for the design of satellite services and systems. Recommendation P. 531-7, Geneva.

Klobuchar, J. A. (1982). Ionospheric Corrections for the Single Frequency User of the Global Positioning System. National Telesystems Conference, NTC'82. Systems for the Eighties. Galveston, Texas, USA (New York: IEEE, 1982).

Kunches, J. M. and Klobuchar, J. A. (2001). Eye on The Ionosphere: GPS after SA. GPS Solutions 4(3), PP. 52-54.

Nava B., P.Coı¨sson, S.M.Radicella (2008). A new version of the NeQuick ionosphere electron density model. Journal of Atmospheric and Solar-Terrestrial Physics 70 (2008) 1856–1862.

NOAA-NGDC (2017). National Centers for Environmental Informations.(https://www.ngdc.noaa.gov/) Accessed (1/4/2017).

Okoh Daniel, Sylvester Onwuneme, Gopi Seemala, Shuanggen Jin, Babatunde Rabiu, Bruno Nava, Jean Uwamahoro (2018). Assessment of the NeQuick-2 and IRI-Plas 2017 models using global and long-term GNSS measurements. Journal of Atmospheric and Solar-Terrestrial Physics. Volume 170, May 2018, Pages 1-10.

Perna L., K. Venkatesh, V.G. Pillat, M. Pezzopane, P.R. Fagundes, R.G. Ezquer, M.A. Cabrera (2018). Bottom side profiles for two close stations at the southern crest of the EIA: Differences and comparison with IRI-2012 and NeQuick2 for low and high solar activity. Advances in Space Research 61 (2018) pages 295–315.

Radicella, S.M., B. Nava, P. Coisson and R. Leitinger (2003). A Flexible 3D Ionospheric Model for Satellite Navigation Applications. 2003-International Symposium on GPS/GNSS, Japan, PP. 305-310.

Radicella, S.M., Leitinger, R., (2001). The evolution of the DGR approach to model electron density profiles. Advances in Space Research 27 (1), 35–40.

Radicella, S.M., Zhang, M.L., (1995). The improved DGR analytical model of electron density height profile and total electron content in the ionosphere. Annali di Geofisica XXXVIII (1), 35–41.

SIDC (2017). (http://sidc.oma.be/sunspot-data/1998,1999,2001). Accessed (1/4/2017).

WDC (2017). World Data Center, Russia. (http://www.wdcb.ru/stp/data/geomagni.ind/kp_ap/) Accessed (1/4/2017)

Received: 2018-03-16,

Reviewed: 2018-07-27,2018-08-23, and 2018-09-10,

Accepted: 2018-09-26.