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Minimizing NeQuick TEC prediction error via data ingestion at three African equatorial stations

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Abstract

NeQuick model is a three dimensional and time dependent ionospheric electron density model that gives as output electron density profile $N(h)$ and via integration the slant TEC (sTEC) for any particular locations on the globe. The model requires as input solar ionizing index in addition to the coordinates of the ray points. The index being used as a proxy to the EUV which is responsible for the ionization of the upper atmosphere is either the smoothed sunspot numbers (R12) or the 10.7 cm solar radio noise flux ($F_{10.7}$). The closer the values of the proxy index to the EUV value, the better the performance of the NeQuick model. We have therefore investigated the improvement of NeQuick via optimization of the $F_{10.7}$ index using GPS sTEC derived data from three stations in the equatorial region of the African sector. In order to achieve this, the root mean square of the difference between the modeled and the observed sTEC values were calculated for a range of values of $F_{10.7}$, and via optimization, the effective $F_{10.7}$ index (i.e. the one that gives the minimum root mean square error or the one that minimizes the error between the observed and the modeled) was obtained for a particular day and for a particular station. The value obtained (i.e. effective $F_{10.7}$), which is a station based value, is then used as ionization index into the NeQuick model for the next two consecutive days. The results obtained showed an improvement in the model performance for these two days although that of the first day, in most cases, is better than that of the second day.

Keywords: Equatorial ionosphere, NeQuick Model, Ionization parameter, effective $F_{10.7}$ index, Total Electron Content.

1. Introduction

NeQuick (Radicella and Leitinger, 2001) is a three dimensional and time dependent ionospheric electron density model developed at the Aeronomy and Radiopropagation

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Laboratory of the Abdus Salam International Centre for Theoretical Physics (ICTP) - Trieste, Italy and the Institute for Geophysics, Astrophysics and Meteorology of the University of Graz, Austria. The input parameters to the model are the coordinate of the receiver (Ray point 1), coordinate of the satellite (Ray point 2), year, month, time of the day, and the ionization index. NeQuick gives as output electron density profile $N(h)$ and via integration the slant TEC (sTEC) for the receiver-to-satellite link.

The ionization index being used as proxy to the Extreme Ultraviolet (EUV) component of the solar radiation responsible for the photo-ionization of the upper atmosphere is the monthly smoothed sunspot number (R12) or the 10.7 cm radio flux ($F_{10.7}$). The performance of the model varies from one geographic location to another but worse performance is expected at the equatorial region (e.g. Oladipo and Schueler, 2012). Just like other global ionosperic models in its class, NeQuick formulation is being improved upon from time to time (Amarante *et al.*, 2005; Leitinger *et al.*, 2005; Nava *et al.*, 2008). Besides the improvement, NeQuick source code is openly available and the code could be modified in order to adapt the model to a particular location or region of interest. To this end, a technique was developed by Nava *et al*., 2005 that involves the improvement of the NeQuick model capabilities by ingestion of experimental data into the model. This technique has been tested (Nava et al., 2006) using both sTEC and critical frequency of the F2 layer (foF_2) data for a single station as well as multiple stations in the north America.

The result showed an improvement in the capability of the model for a single station approach for both sTEC and foF_2 data and a better improvement for only sTEC for multiple stations. It is important to mention here that equatorial region of the ionosphere is the most difficult region to model because of the equatorial anomaly which is a special feature of this region. It is worthwhile to check the performance of this method in the equatorial region of the ionosphere. This study therefore focuses on a single station approach using data from three stations in the equatorial region of the African sector. We also explored, in this study, the possibility of using the effective $F_{10.7}$ index obtained for a particular day to improve the model capability for the next two consecutive days.

2. Data and Analyses

The data used for this study are the GPS data from three stations located in the equatorial region in the African sector. The stations are Ilorin in Nigeria (lat = 8.42 °, long = 4.67 °, Dip = - 3.74 °), Libreville in Gabon (lat = 0.3523 °, long = 9.6698 °, Dip = - 15.94 °) and Mbarara in Uganda (lat = - 0.6015 °, long = 30.7379 °, Dip = - 10.86 °). Ilorin data were obtained from SCINDA receiver located at Ilorin while data for Libreville and Mbarara were obtained from International GNSS Network Service (IGS) network of stations with open access at http://garner.ucsd.edu/pub/rinex/. The data used are for 2008 a year of low solar activity and the months of March and December were selected as representative months for Equinox and Solstice seasons respectively. Figure 1 shows the map of Africa indicating the location of the three stations with respect to the magnetic equator. The Slant TEC (sTEC) values were obtained from GPS RINEX files using GPS TEC retrieval software developed by L. Ciraolo of the Istituto di Fisica Applicata "Carrara" (IFAC-CNR) Firenze, Italy. The full description of the algorithm can be found in Ciraolo *et al*. (2007).

Solar ionization index used as input into NeQuick is $F_{10.7}$ index and the values are available at http://www.wdcb.ru/stp/data/solar.act/flux10.7. The idea of the effective ionization index is due to the fact that the solar ionization indices widely used as proxies (i.e. R12 and $F_{10.7}$) are far from the EUV part of the solar radiation spectrum that is majorly responsible for the formation of the ionosphere. Effective sunspot number SSNe parameter as described by Secan and Wilkinson (1997) is the value of SSN that when used as input to the International Union of Radio Science (URSI) foF_2 model, gives a weighted zero-mean difference between the observed and the modeled foF_2 values. In a similar way, effective $F_{10.7}$ index was obtained for a particular day and station i.e. the value of $F_{10.7}$ that when used as input to the NeQuick model minimizes the error between the modeled and the experimental sTEC values. To achieve this, an algorithm was developed, which was implemented MatLab codes, which calls NeQuick as a subroutine in order to obtain the effective $F_{10.7}$ index. This is done by setting a range of values of $F_{10.7}$ index, in most of the cases as ± 30 of the observed $F_{10.7}$ for a day for the minimization /optimization process. It is important to note that the least value of $F_{10.7}$ index that NeQuick can take as input is about 35 and that the algorithm took cognizance of this. For each value of $F_{10.7}$ in the range defined above, Root Mean Square Error (RMSE) is computed for the difference between the observed sTEC ($sTEC_{obs}$) and sTEC obtained with NeQuick in $F_{10.7}$ mode ($sTEC_{\mathrm{mod}}(F_{10.7})$) as indicated in Eqn. 1.

$$RMSE(F_{10.7\,j}) = \sqrt{\frac{\sum_{i=1}^{n}(sTEC^{i}_{obs} - sTEC^{i}_{\mathrm{mod}}(F_{10.7\,j}))}{n}}, \tag{1}$$

where $sTEC^{i}_{obs}$ are the observed sTEC values for a day and $sTEC^{i}_{\mathrm{mod}}$ are the corresponding model values as a function of $F_{10.7\,j}$, and $F_{10.7\,j}$ are the set of $F_{10.7}$ values within the range (i.e. ± 30 of the observed $F_{10.7}$ in step interval of 0.1) .

The value of $F_{10.7\,j}$ index, within the range, that minimizes RMSE value as defined in equation 1 is obtained as the effective $F_{10.7}$ index. This value is then used as input ionization index for the next two consecutive days. The results obtained were compared with the one for which the observed $F_{10.7}$ index was used as input into the model.

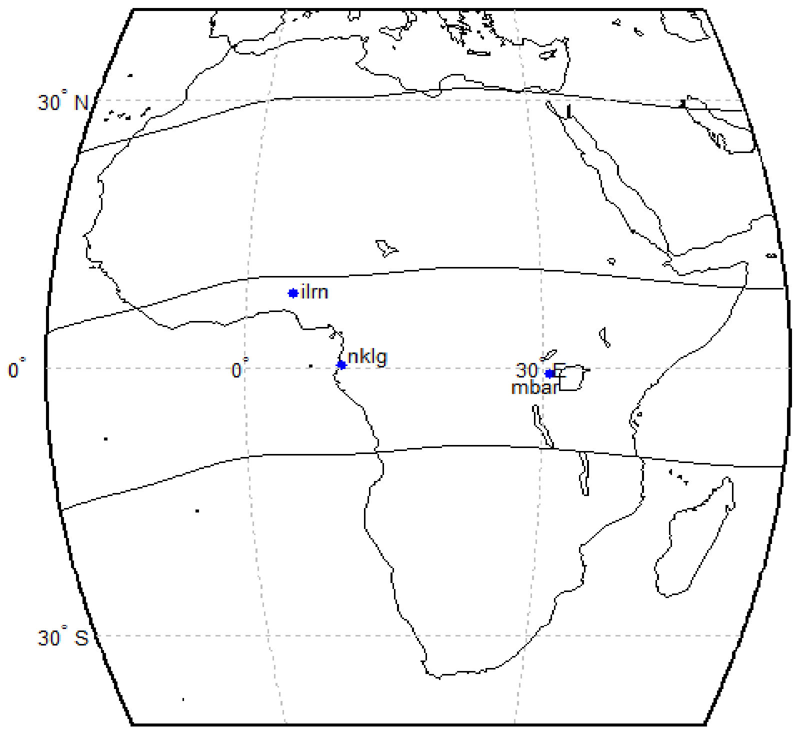

Figure 1: Map of Africa indicating the location of the three stations used in this study i.e. Ilorin (ilrn), Libreville (nklg) and Mbarara (mbar). The solid lines are the geomagnetic lines drawn at -20 °, 0 ° and 20 °.

3. Results and Discussions

This study was carried out using GPS data from three stations for March and December, 2008. For each of these months, three consecutive quite days were used since the NeQuick model gives quiet time monthly average values. The quiet days for the two months were obtained from international quiet days available at http://www.ga.gov.au/oracle/geomag/iqd_form.jsp. Results for March at Mbarara and December at Ilorin are presented in details. However, the summary of the whole study is also presented.

Figure 2 shows diurnal plots of modeled and observed sTEC for March 3 and March 4, 2008 at Mbarara. The upper panels (i.e. a and c) are for the observed and NeQuick modeled values in standard mode while the lower panels (i.e. b and d) are for the observed and NeQuick modeled values in effective mode. The effective $F_{10.7}$ index value obtained using data of March 2, 2008 was used to drive NeQuick in effective mode for March 3 and March 4, 2008. It is very clear from the plot that NeQuick modeled values in effective mode are closer to the observed values than NeQuick modeled values in standard mode on both days.

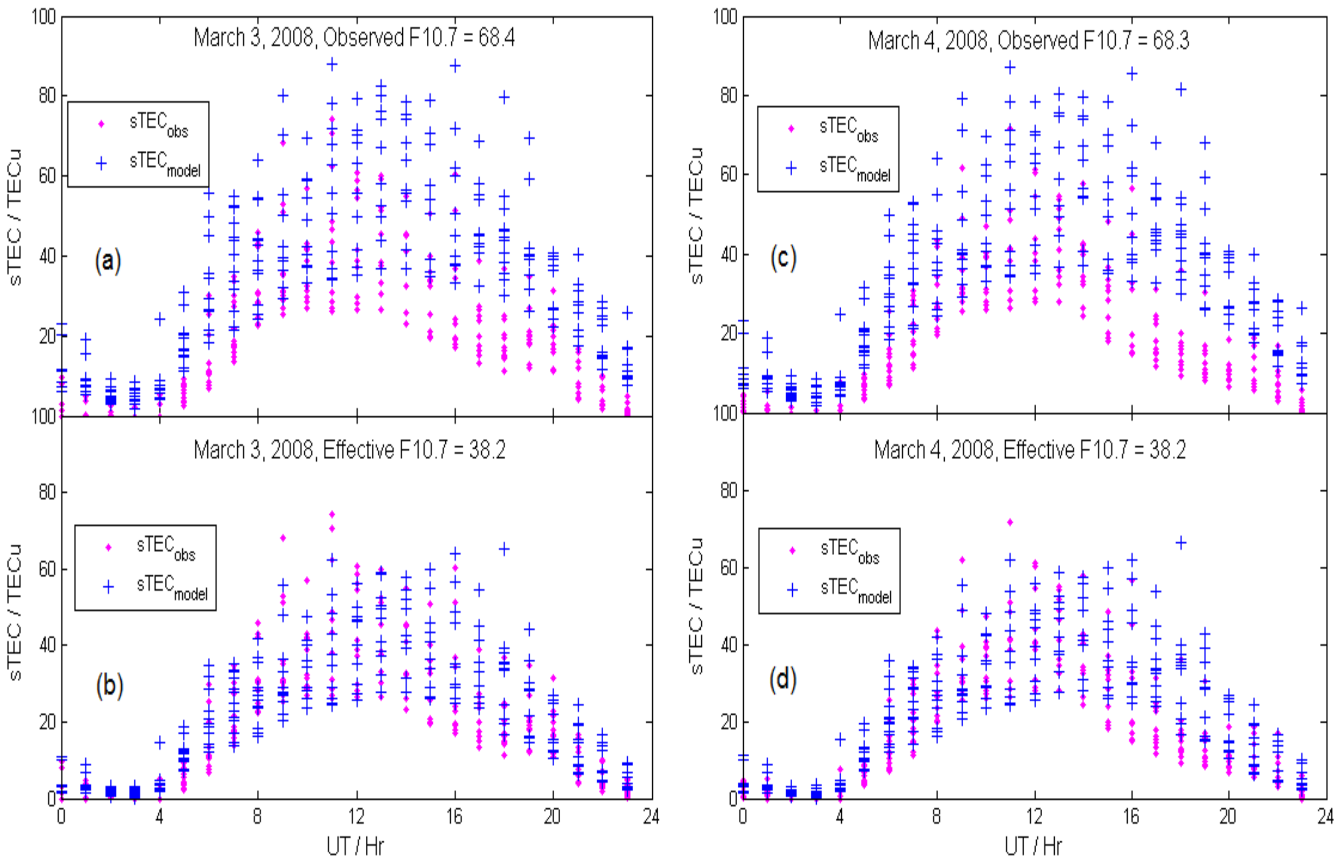

Figure 2: Diurnal plots of modeled and observed sTEC in TECu at Mbarara for March 3, 2008 for (a) NeQuick run in standard mode and (b) for NeQuick run in effective mode. Panel (c) is for NeQuick in standard mode and

(d) for NeQuick in effective mode for March 4, 2008. The effective $F_{10.7}$ used for these two days was obtained on March 2, 2008, Modeled sTEC values are closer to the observed values when NeQuick is run in effective mode than when run in standard mode.

Figure 3 shows the sTEC error distribution plots for the results shown in Figure 2. The error in this case is defined as the difference between the modeled values and the observed values. Daily average error is also indicated on each plot. The error for the NeQuick in effective mode for March 3 is 2.99 TECu and that of March 4 is 4.77 TECu. These indicate a better performance over NeQuick in standard mode with error value of 14.89 TECu and 16.61 TECu for March 3 and March 4 respectively. In terms of the spread of the error, the values for NeQuick in effective are closer to normal distribution than the values for the NeQuick in standard mode for both days. However, the performance of NeQuick in effective mode is better on March 3 compared to that of March 4.

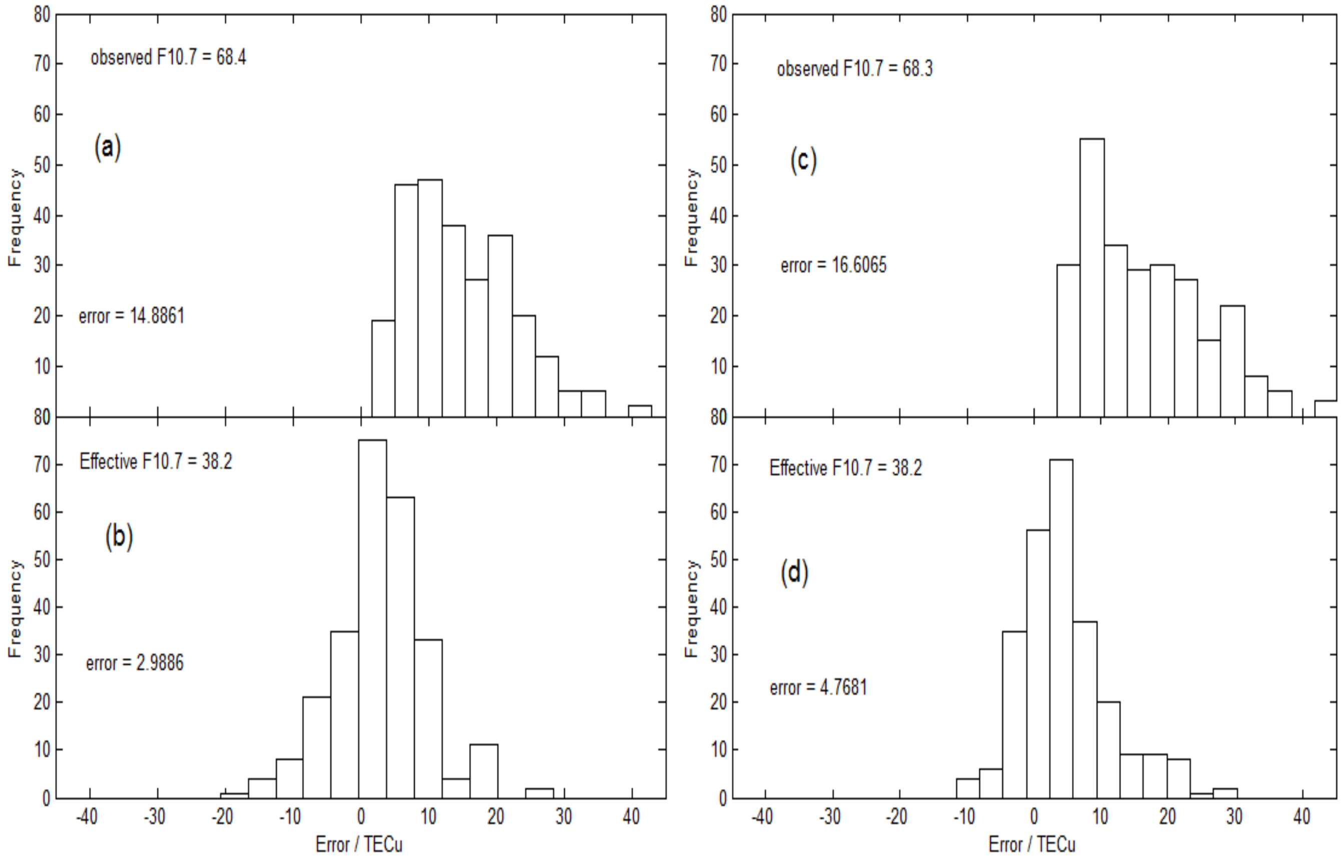

Figure 3: sTEC error distribution for the plots in Figure 2. Although positive skewness is observed in all the plots, distribution of error for NeQuick in effective mode is closer to that of a normal distribution.

Figure 4 shows diurnal plots of modeled and observed sTEC for December 13 and 14, 2008 at Ilorin. Observed $F_{10.7}$ value was used to drive NeQuick for December 13 (Fig. 4a) and December 14 (Fig. 4c) while the effective $F_{10.7}$ value obtained using data for December 12 was used to drive NeQuick on December 13 (Fig. 4b) and December 14 (Fig. 4d). The performance of NeQuick run in effective mode can be seen clearly in this plot when compared with NeQuick run in standard mode. sTEC values are closer to the observed values when NeQuick is run in effective mode than when it is run in standard mode. Similarly, when we compare the results of NeQuick in effective mode for December 13 with that of December 14, performance on December 13 seems to be better than that on December 14. This implies that as we move further away from the day the effective $F_{10.7}$ is obtained, the effectiveness of it in terms of the performance of NeQuick degraded.

Figure 5 shows the sTEC error distribution for the plots in Figure 4. Panels (a) and (c) are when NeQuick was driven with observed $F_{10.7}$ value for each day of December 13 and December 14 respectively while panels (b) and (d) are when NeQuick was driven with the effective $F_{10.7}$ value obtained on December 12, 2008. Daily average error is also indicated on each plot. The distribution of error around the zero TECu shows how close the modeled values are to the experimental values i.e. the closer the distribution of errors to normal distribution the better the performance. The distribution of error for NeQuick in effective mode is closer to normal distribution and the errors are, though not perfectly spread around zero TECu mark. This is true for the two days for NeQuick in effective mode. In effective mode, the result on December 13 is closer to normal distribution than that of December 14. However, that of the NeQuick driven with the observed $F_{10.7}$ is not evenly spread about the zero TECu mark (i.e. a clear positive skewness) for the two days. In terms of the daily average error value, 3.45 TECu and 4.89 TECu were obtained for December 13 and December 14 respectively for NeQuick in effective mode while that of NeQuick driven with observed $F_{10.7}$ value are 13.34 TECu and 14.45 TECu for December 13 and 14 respectively. This shows the possible improvement in the performance of the NeQuick model when experimental data are ingested into it.

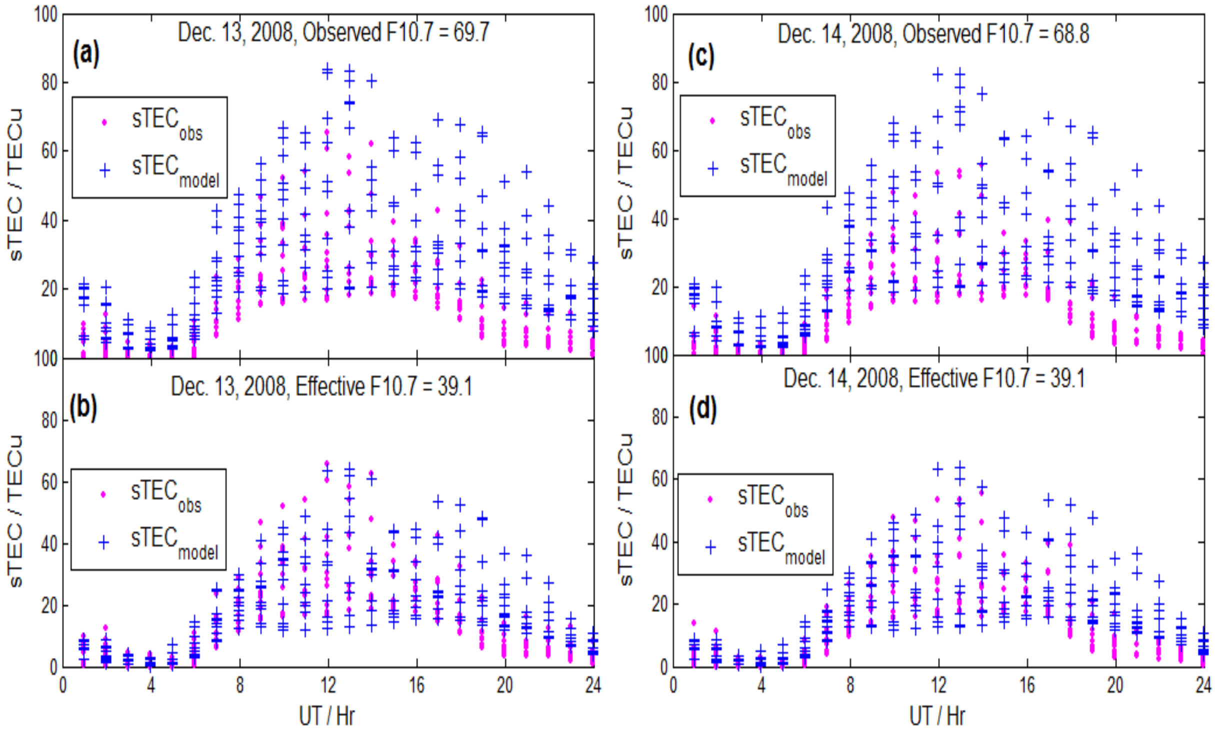

Figure 4: Diurnal plots of modeled and observed sTEC in TECu at Ilorin for December 13, 2008 (a & b) and December 14, 2008 (c & d) at Ilorin, Nigeria. Panels a & c are for Modeled sTEC for NeQuick in standard mode and observed sTEC while b & d are for Modeled sTEC for NeQuick in effective mode and observed sTEC. Effective $F_{10.7}$ used for the two days was obtained on December 12, 2008. Modeled sTEC for NeQuick in effective mode (i.e. b & d) are closer to the observed values than modeled sTEC for NeQuick is standard mode.

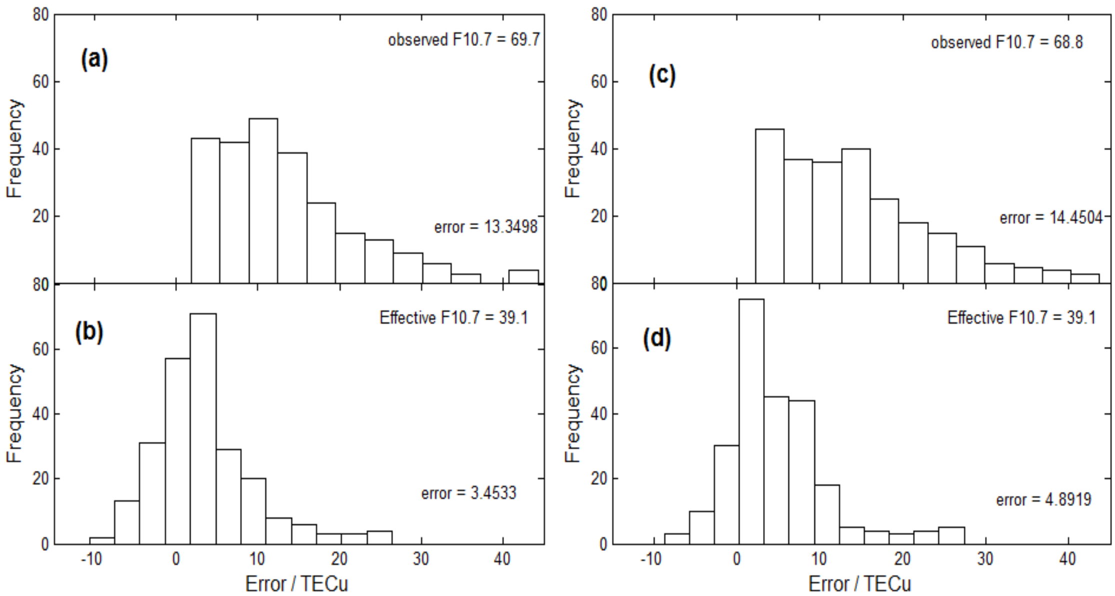

Figure 5: sTEC error distribution for the plots in Figure 4. Although positive skewness is observed in all the plots, distribution of error for NeQuick in effective node is closer to that of a normal distribution.

The summary of the results obtained for the three stations investigated using data for March and December 2008 is shown in Table 1. In March 2008, effective $F_{10.7}$ was obtained for each station using data of March 2, 2008. Although the values are station by station values, the values were found to be equal to 38.2 for all the three stations investigated. This value was then used as input in running NeQuick in effective mode for March 3 and March 4, 2008. As indicated in Table 1, error in TECu for March 3 for NeQuick in effective mode is 10.18 TECu, 2.99 TECu and 1.87 TECu for Ilorin, Mbarara and Libreville respectively compared to that of NeQuick in standard mode with error 19.76 TECu, 14.89 TECu and 12.60 TECu for Ilorin, Mbarara and Libreville respectively. This shows an improvement over NeQuick in standard mode i.e. when observed $F_{10.7}$ was used as input ionization parameter. The results of March 4 (i.e. when effective $F_{10.7}$ obtained on March 2 was used as input ionization parameter) are similar to that of March 3 in terms of improvement over NeQuick in standard mode.

Similarly for December 2008 study; effective $F_{10.7}$ (i.e. station – by – station value) was obtained using data of December 12, 2008 for the three stations. Effective $F_{10.7}$ of 39.1 was obtained for all the three stations. The value was then used as input ionization parameter on December 13 and December 14, 2008. Daily average error obtained are 3.45 TECu, 5.45 TECu and 3.95 TECu for Ilorin, Mbarara and Libreville respectively for NeQuick run in effective mode and 13.35 TECu, 13.18 TECu and 13.59 TECu for NeQuick run in standard mode. This indicates that the prediction of NeQuick run in effective mode gives sTEC values that are closer to the observed sTEC values when compared with the one run in standard mode. This is also true for December 14, 2008 as indicated in Table 1.

Table 1: Summary of the results obtained, in terms of the performance of NeQuick, for the three stations investigated. Daily average values of Error in TECu for NeQuick run in standard mode and that of NeQuick run effective mode are indicated as well as the effective $F_{10.7}$ obtained. It is obvious that NeQuick run in effective mode gives a better prediction compared to NeQuick run in standard mode for all the stations and for the two consecutive days after the day effective $F_{10.7}$ was obtained

Effective $F_{10.7} = 38.2$, obtained on March 2, 2008				
Station Name	March 3, 2008 Observed $F_{10.7} = 69.2$		March 4, 2008 Observed $F_{10.7} = 68.4$	
	Error / TECu (Standard Mode)	Error / TECu (Effective Mode)	Error / TECu (Standard Mode)	Error / TECu (Effective Mode)
Ilorin	19.76	10.18	19.42	9.93
Mbarara	14.89	2.99	16.61	4.77
Libreville	12.60	1.87	11.89	1.03
Effective $F_{10.7} = 39.1$, obtained on December 12, 2008				
Station Name	Dec. 13, 2008 Observed $F_{10.7} = 69.7$		Dec. 14, 2008 Observed $F_{10.7} = 68.8$	
	Error / TECu (Standard Mode)	Error / TECu (Effective Mode)	Error / TECu (Standard Mode)	Error / TECu (Effective Mode)
Ilorin	13.35	3.45	14.45	4.89
Mbarara	13.18	5.45	14.80	7.39
Libreville	13.59	3.98	15.87	6.70

The results obtained in this current study have shown that the station based effective $F_{10.7}$ value obtained for a particular day has the potential to improve the performance of NeQuick, in terms of sTEC prediction, for the next two consecutive days. It is important to mention that the major input to the NeQuick model is the ionization parameter (i.e. $F_{10.7}$ or R12 index). This value gives the level of ionization for a particular day - the closer the value to the actual ionization index (i.e. EUV index), the better the performance of the NeQuick model's prediction. The intensity of solar radiation (i.e. EUV) reaching the upper atmosphere varies from one latitudinal region to another. Therefore, there is the need to customize the value to a particular location via the data ingestion procedure. The procedure is towards adapting the model to a particular region.

Observation from this study also showed that for the three stations, all within the equatorial region in the African sector, the same value of effective $F_{10.7}$ is required. The implication of this result is that a single effective $F_{10.7}$ index obtained using data from just one station for a particular day could be used to improve the performance NeQuick for the next two days – not just over the station alone but even within the same region.

4. Conclusion

Performance of single station NeQuick data ingestion method in the equatorial region of the African sector was investigated using data from three stations. The study was done using data for quiet days for the months of March and December 2008. The results obtained in this study for the three stations clearly show that the capability of the NeQuick model in terms of sTEC prediction could be enhanced when it is driven by the effective $F_{10.7}$ index. Specifically, it was observed in this study that the effective $F_{10.7}$ obtained using experimental sTEC values for a particular day via a single station approach could be used to enhance the capability of NeQuick for the next two successive days. Another important observation is the fact that, though the effective $F_{10.7}$ value was obtained station – by – station, the value is found to be equal for the three stations for a particular month.

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References

Amarante, G.M., Radicella, S.M., Nava, B. and Coïsson, P. (2005): Validation of a method for ionospheric electron density reconstruction by means of vertical incidence data during quiet and storm periods. *Annales Geophysicae*. **48**(2), 321 - 326.

Ciraolo, L., Azpilicueta, F., Brunini, C., Meza, A. and Radicella, S. M. (2007): Calibration Errors on Experimental Slant Total Electron Content (TEC) Determined with GPS. *Journal of Geodesy*. **81**(2), 111-120.

Leitinger, R., Zhang, M. L. and Radicella, S. M. (2005): An improved bottomside for the ionospheric electron density model NeQuick. *Annales Geophysicae*. **48**(3), 525–534.

Nava, B., Coïsson, P., Amarante, G.M., Azpilicueta, F. and Radicella, S.M. (2005): A model assisted ionospheric electron density reconstruction method based on vertical TEC data ingestion. *Annales Geophysicae*. **48**(2), 313 - 320.

Nava, B., Radicella, S. M., Leitinger, R. and Coïsson, P. (2006): A near-real-time model-assisted ionosphere electron density retrieval method. *Radio Science*. **41**, RS6S16.

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

Oladipo, O.A and Schüler, T (2012): GNSS single frequency ionospheric range delay corrections: NeQuick data ingestion technique. *Advances in Space*. **50**(9), 1204 – 1212.

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

Secan, J.A. and Wilkinson, P.J. (1997): Statistical studies of an effective sunspot number. *Radio Science*. **32** (4), 1717 – 1724.