Application of neural networks to South African GPS TEC modelling

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Abstract

The propagation of radio signals in the Earth's atmosphere is dominantly affected by the ionosphere due to its dispersive nature. Global Positioning System (GPS) data provides relevant information that leads to the derivation of total electron content (TEC) which can be considered as the ionosphere's measure of ionisation. This paper presents part of a feasibility study for the development of a Neural Network (NN) based model for the prediction of South African GPS derived TEC. The South African GPS receiver network is operated and maintained by the Chief Directorate Surveys and Mapping (CDSM) in Cape Town, South Africa. Vertical total electron content (VTEC) was calculated for four GPS receiver stations using the Adjusted Spherical Harmonic (ASHA) model. Factors that influence TEC were then identified and used to derive input parameters for the NN. The well established factors used are seasonal variation, diurnal variation, solar activity and magnetic activity. Comparison of diurnal predicted TEC values from both the NN model and the International Reference Ionosphere (IRI-2001) with GPS TEC revealed that the IRI provides more accurate predictions than the NN model during the spring equinoxes. However, on average the NN model predicts GPS TEC more accurately than the IRI model over the GPS locations considered within South Africa.

1. Introduction

The non-linear variability of the ionospheric parameters due to the complex processes that occur within the ionosphere's different layers causes significant changes in the performance of different systems such as satellite navigation and communications, space weather forecasts and GPS surveying ([Kouris et al., 2004], [Tulunay et al., 2004] and [Tulunay et al., 2006]). The existence of the ionosphere depends on the ultra violet (UV) radiation from the sun which ionises a fraction of the neutral Earth's atmosphere ([Klobuchar, 1991] and [Reddy, 2002]). Due to the multilayered structure of the ionosphere, electromagnetic waves such as GPS signals are affected differently as they propagate through the different layers. TEC, which can be considered as the ionosphere's measure of ionisation (Meggs, 2005), is defined as the number of electrons in a column of cross-sectional area 1 m^2 along a path of the signal through the ionosphere. It is expressed in TECU, where 1 TECU is equivalent to 1×10^{16} electrons/m^2.

As a GPS signal travels through the ionosphere at two L-band GPS frequencies L1 (1575.42 MHz) and L2 (1227.60 MHz), a time delay is experienced which, to the first approximation, is directly proportional to TEC and inversely proportional to the square of its frequency (Hofmann-Wellenhof et al., 1992) as follows:

$$dt = \left(\frac{40.28}{cf^2}\right) \times TEC \quad (1)$$

where dt is the ionospheric time delay, c is the light velocity (3.0×10^8 m/s) and f is the wave propagation frequency.

The parameters which are known to influence GPS TEC are solar and magnetic activities, geographical position of the receiver, line of sight for the GPS satellite, diurnal and seasonal variations ([Hofmann-Wellenhof et al., 1992] and [Bhuyan and Borah, 2007]).

The technique of neural networks (NNs) has been found promising in modelling parameters that exhibit non-linear characteristics such as the prediction of solar cycle 23 (Conway et al., 1998) and the ionospheric peak electron density in the equatorial anomaly regions (Sarma and Mahdu, 2005). NNs have also been widely used in ionospheric studies involving TEC modelling using GPS data (Hernandez-Pajares et al., 1997), time dependent TEC predictions and forecasting using Faraday-rotation derived TEC (Xenos et al., 2003). Recently, Leandro and Santos (2007) used NNs in vertical GPS TEC computation and modelling, and Tulunay et al. (2006) utilised the same technique in the forecasting of TEC maps.

This paper is an extension of the work of Habarulema et al. (2007) which presents some of the preliminary results obtained using NNs to predict South African GPS derived TEC. The main intention of this work is to establish the suitability of NNs in predicting TEC values over locations where data was not included in the NN training. In addition, this work provided background material for the quest towards the development of a TEC prediction model for Southern Africa. VTEC values were calculated using the ASHA model from dual frequency GPS observations (Opperman et al., 2007). In the NN training and validating processes, two South African GPS stations were separately considered: Sutherland (32.38°S, 20.81°E), which is an International GPS Service (IGS) station managed by the Hartebeesthoek Radio Astronomy Observatory (HartRAO) and Springbok (29.67°S, 17.88°E), a station in the network of GPS receiver stations of the Chief Directorate Surveys and Mappings (CDSM). VTEC values from two other South African GPS stations located at Cape Town (33.95°S, 18.47°E) and Upington (28.41°S, 21.26°E) were predicted using results obtained from NN models at Sutherland and Springbok, respectively. Results for Upington were compared with ionosonde TEC (ITEC) from a very nearby ionosonde station located at Louisvale (28.5°S, 21.2°E). Fig. 1 is the South African map showing the four GPS receiver stations used and the location of the ionosonde.

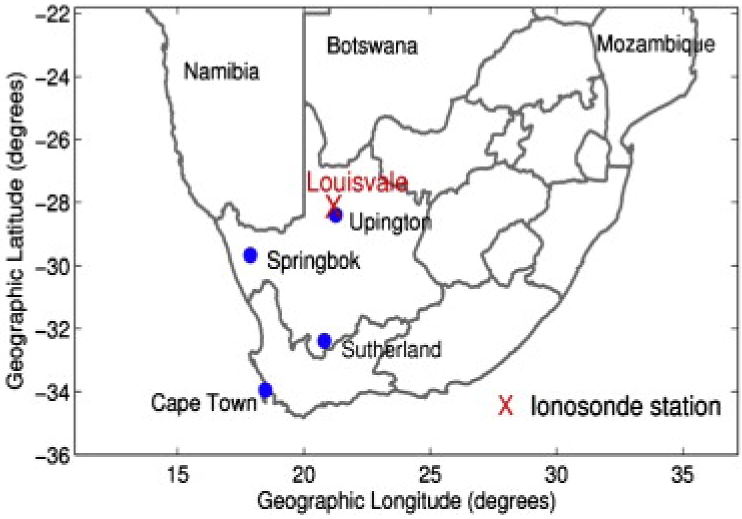


Fig. 1. A South African map showing the four dual frequency GPS receiver stations and the location of the ionosonde used in this study.

2. The ASHA model

The ASHA model calculates TEC at the ionospheric pierce point (IPP) from dual frequency GPS observations using a spherical harmonic expansion according to the following mathematical expression (Opperman et al., 2007);

$$TEC(\lambda, \phi) = \sum_{n=0}^{N} \sum_{m=0}^{n} \overline{P}_{nm} \cos(\phi)[a_{nm} \sin(m\lambda) + b_{nm} \cos(m\lambda)] \tag{2}$$

where λ is the IPP Sun-fixed longitude, ϕ is the IPP co-latitude, $\overline{P}_{nm}$ are the normalised associated Legendre functions, a_{nm} and b_{nm} are the spherical harmonic coefficients estimated from a weighted least squares solution, n and m are the degree and order of the spherical expansion, respectively.

The slant TEC (TEC along the line of sight) is then converted to VTEC at the IPP by assuming the ionosphere to be a single layer (usually referred to as the Single Layer Model, SLIM) with the following cosec mapping function (Hofmann-Wellenhof et al., 1992);

$$T_s = \frac{T_v}{\cos(z')}, \quad \sin(z') = \frac{R_E}{R_E + H} \sin(z) \tag{3}$$

T_s and T_v are the slant and vertical TEC, respectively; R_E = 6378.134 km is the Earth radius; H is the single layer model height of 350 km; z and z' are the zenith angles at the observing location and IPP, respectively.

The ASHA model estimates TEC and eliminates the differential clock biases (DCBs). It was adapted from Schaer (1999) global model to be used as a regional model using data from a local GPS receiver network and was chosen to estimate single station TEC results for comparative purposes with ionosonde measurements. In the ASHA model, the DCBs from both satellite transmitters and GPS receivers are estimated along with the spherical harmonic coefficients using the least squares method. A full solution of this is discussed in Opperman et al. 2007.

The transformation of GPS observations from Earth-fixed frame to Sun-fixed longitude system allows a longitudinal coverage of 360° over a 24 h time period (Bergstrand and Haas, 2004), thus the spatial and temporal changes of the ionosphere with respect to GPS receivers are taken into account. In addition, the ionosphere's variation is much slower in the Sun-fixed reference frame compared to the Earth-fixed reference frame (Mannucci et al., 1995). For a detailed discussion about the ASHA model, the reader is referred to (Opperman et al., 2007) and (Opperman, 2007).

3. Data processing for NN applications

GPS TEC values were calculated from the dual frequency GPS receiver network using the ASHA model at intervals of 60 s. For the purpose of this work, hourly values of TEC were extracted from the data set generated by the ASHA model and used in NN modelling. The dataset used to train the NN consisted of the TEC values at each hour for the period 2001–2004. A reduced dataset for the feasibility study was deliberately used in order to reduce training time of the NN. The input space for the NN was derived from the parameters known to influence TEC such as solar activity, magnetic activity, seasonal variation, diurnal variation and geographical location of the GPS receivers.

Solar activity and magnetic activity variations were represented by a 4-month running mean of the daily sunspot number (R4) and the running mean of the previous eight 3-hourly magnetic A index values (A8) derived from the K-index recorded at the Hermanus Magnetic Observatory, South Africa (Habarulema et al., 2007). A detailed discussion about the determination of appropriate input parameters to represent solar and magnetic activities suitable for TEC modelling over South Africa is found in Habarulema et al. (2007). The seasonal and diurnal variations as represented by day number (DN) and hour (HR) were each split into two cyclic components to allow numerical continuous trend of the data ([Williscroft and Poole, 1996] and [Poole and McKinnell, 2000]) as follows:

(4)

$$DNS = \sin\left(\frac{2\pi \times DN}{365.25}\right) \quad DNC = \cos\left(\frac{2\pi \times DN}{365.25}\right)$$

(5)

$$HRS = \sin\left(\frac{2\pi \times HR}{24}\right) \quad HRC = \cos\left(\frac{2\pi \times HR}{24}\right)$$

where *DNS*, *DNC*, *HRS* and *HRC* are the sine and cosine components of *DN* and *HR*, respectively.

4. The neural network technique

NNs are interconnected groups of artificial neurons that are used to learn data patterns using computational modelling given both known input and output parameters (Fausett, 1994). A NN consists of input, hidden and output layers. In each layer, there are nodes or units that calculate numerical values which are dependant on the number of units present in the entire network connection (Conway et al., 1998). The main advantage of NNs is that given enough historic data, they are capable of learning and generalising physical aspects which exhibit non-linear behaviour when identical but not necessarily the same data is introduced ([Fausett, 1994] and [Bishop, 1995]). NNs have different forms and a wide range of applications as discussed in several sources ([Haykin, 1994], [Fausett, 1994] and [Bishop, 1995]). For this work, we have used a single hidden layered feed forward network (SFFNN) with a back propagation algorithm. Our SFFNN has one input layer, one hidden layer and one output layer. The choice of this network is based on the work done by Habarulema et al. (2007) which describes the first application of predicting TEC over South Africa using NNs. It has also been shown that including more than one hidden layer does not lead to much difference in the accuracy of results (Haykin, 1994), although more hidden layers may make training easier in some cases (Fausett, 1994) depending on the amount of data under consideration. The input layer consists of six nodes or neurons corresponding to six inputs (in this work). Using the procedure of adding a neuron to the hidden layer, training the NN, testing it and finally comparing the predicted TEC with the derived GPS TEC, the number of hidden neurons that gave the optimum solution was determined to be nine. Thus the NN configuration used in this study is 6:9:1, where one is the neuron within the output layer. The root mean square error (RMSE) method has been used to determine the optimum solution. This method (RMSE) has been successively used as a means to determine optimum parameters during ionospheric peak electron density predictions ([Williscroft and Poole, 1996], [McKinnell, 2002] and [Oyeyemi et al., 2006]), solar and geomagnetic activity data predictions (Macpherson et al., 1995) and in solar cycle predictions using neural networks (Conway et al., 1998).

5. Results and discussion

For each NN trained the RMSE value between the GPS TEC and the predicted TEC was computed. It should be noted that the International Reference Ionosphere (IRI) produces monthly median values for TEC and the NN gives the best possible average predicted TEC for the given geophysical conditions. Thus, in order to compare with the current available and mostly used model, our results are shown against the IRI-2001 predictions.

5.1. Sutherland (32.38°S, 20.81°E) and Cape Town 33.95°S, 18.47°E)

Hourly values of TEC were extracted for a period of four years (2001, 2002, 2003 and 2004) from the data set and used in NN training and validating processes. The total number of inputs were 6 (DNS, DNC, HRS, HRC, R4 and A8) and the architecture of the network was single layered with nine hidden nodes in the hidden layer. The constructed hourly NN model for Sutherland was used to predict GPS TEC values for the GPS receiver station located at Cape Town (33.95°S, 18.47°E) during equinoxes and solstices as shown in Fig. 2. GPS TEC values at 22h00 UT, 04h00 UT and 10h00 UT for Cape Town were also predicted and results compared graphically with the corresponding TEC values from the IRI model (denoted as IRI-2001) as shown in Fig. 3. From Fig. 3, large TEC variations are observed during autumn and spring equinoxes while TEC generally decreases in winter. TEC also depletes on the night side of the Earth due to the recombination of free electrons with the ions and thus diurnal variation is the strongest driving mechanism for TEC changes (Klobuchar, 1991). There is a general agreement between GPS TEC and IRI TEC in the shape of seasonal variations as seen in Fig. 3. A similar seasonal trend has been reported by Mosert et al. (2007) using data from Ebro (40.8°N, 0.5°E). The significant difference observed where GPS TEC is greater than IRI TEC is due to the altitude at which TEC is estimated in both cases (altitudes are about 20 200 km and 2000 km for GPS TEC and IRI TEC, respectively). The difference in TEC is compatible with the plasmaspheric electron content present in GPS TEC (Mosert et al., 2007).

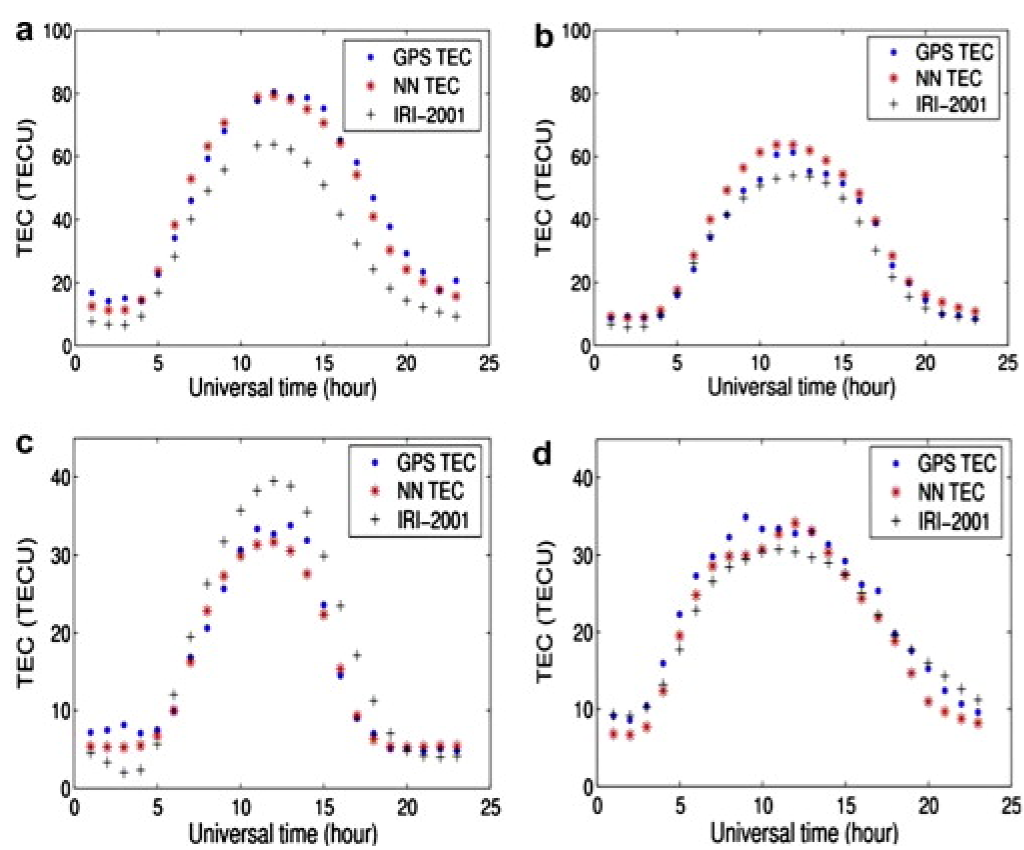


Fig. 2. Comparison of GPS TEC with TEC predictions from the IRI-2001 and NN model over Cape Town (33.95°S,18.47°E) during equinoxes: (a) March 20, (b) September 23 and solstices: (c) June 22, (d) December; all in 2002.

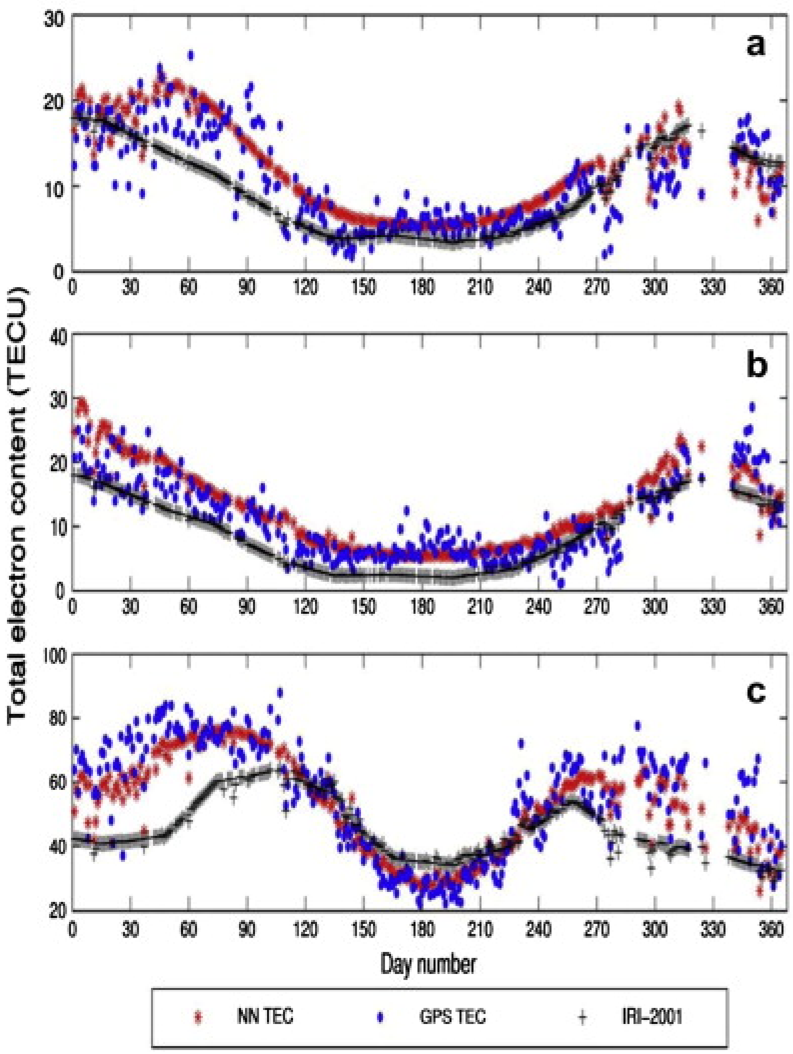


Fig. 3. Comparison of GPS TEC, NN TEC and IRI TEC values over Cape Town (33.95°S, 18.47°E) in 2002 at midnight (22h00 UT), sunrise (04h00 UT) and midday (10h00 UT).

Fig. 2 shows the comparison of hourly GPS TEC values from the ASHA model with the corresponding IRI-2001 and NN TEC predictions for days representing equinoxes and solstices over a mid-latitude GPS station located at Cape Town (33.95°S, 18.47°E). It is observed that IRI-2001 under predicts GPS TEC on day 79 and over predicts GPS TEC on day 173 (between ~08h00 UT and 17h00 UT) in 2002 as shown in Fig. 2(a) and (c). The maximum difference of ~17 TECU between GPS TEC and IRI TEC is observed at 12h00 UT as seen in Fig. 2(a), and this can be considered as part of the contribution of the plasmasphere in GPS TEC at this particular time, the remaining difference being due to other sources, probably errors introduced into the GPS TEC value by assuming the ionosphere to be a single layer of fixed height and the assumptions made about the topside profile in the IRI model. GPS TEC values compare favourably well with IRI TEC values in Fig. 2(b) and (d) with maximum differences of ∼8 TECU and 5 TECU observed at 11h00 UT and 09h00 UT, respectively.

Table 1 shows the RMSE values between the GPS TEC and TEC values as predicted by the NN and IRI-2001 models for equinox and solstice days. The NN model predicts GPS TEC more accurately during the winter solstice (June 22) than in other seasons. The IRI-2001 model provides a more accurate prediction during the spring equinox (September 23) than the NN model. A statistical observation can be made from Table 1 that the average error difference between the NN TEC and GPS TEC as quantified in terms of RMSE is ∼3 TECU in contrast to ∼6 TECU RMSE between the IRI TEC and GPS TEC during equinoxes and solstices. However taking into account that one station has been analysed here, more work should to be done to confirm this result. The over prediction of GPS TEC by the IRI model during winter as shown in Fig. 2(c) and Fig. 3(c) may be due to the historical fact that there is generally less data available over the Southern African region (McKinnell, 2002). Very recently, Moeketsi et al. (2007) compared GPS TEC derived using the University of New Brunswick (UNB) ionospheric mapping technique and IRI TEC from IRI 2001, over a mid-latitude GPS receiver station located at Sutherland (32.38°S, 20.81°E), South Africa and also obtained an overprediction (∼ 05h00 UT–10h00 UT) for day 103 in 2003. At the equinoxes, maximum TEC values of ∼80 TECU and 60 TECU occur at 12h00 UT for March 20 and September 23, 2002, respectively. On the other hand, maximum TEC values of ∼33 TECU and 34 TECU during the solstices occurred at 13h00 UT and 09h00 UT for June 22 and December 21, 2002, respectively. In all cases (equinoxes and solstices) a gradual morning rise and evening decrease of TEC is observed and generally, maximum TEC occurs between 10h00 UT and 12h00 UT.

Table 1.

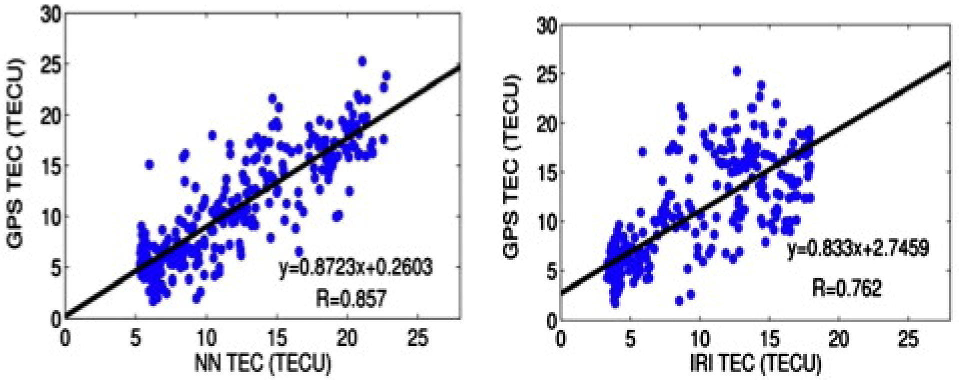
Computed RMSE values (TECU) for each of the four days representing equinoxes and solstices in 2002 over Cape Town (33.95°S, 18.47°E).

Date of the month in 2002	**RMSE (TECU) between**	
	NN TEC and GPS TEC	**IRI TEC and GPS TEC**
March 20	3.880	15.086
June 22	1.687	4.690
September 23	4.061	3.866
December 21	2.520	2.702

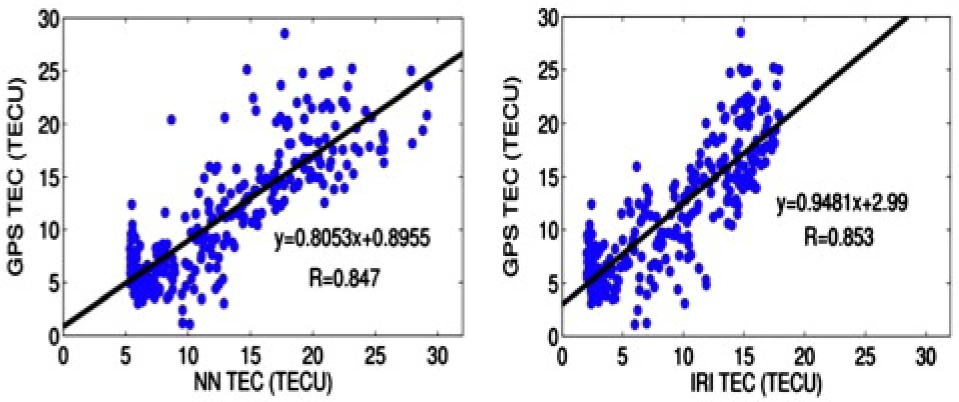
Fig. 4 shows the scatter plot for GPS TEC with corresponding TEC predictions from the NN and IRI-2001 models over Cape Town (33.95°S, 18.47°E) in 2002, with lines of best fit inserted for all cases. Correlation coefficients give reliability levels of the NN and IRI models to predict GPS TEC. From the considered times, GPS TEC is highly correlated to NN TEC at 10h00 UT with a correlation coefficient (R) of 0.905. The high average plasmaspheric contribution of ∼4.44 TECU is also observed at 10h00 UT with reference to IRI TEC as shown in Fig. 4(c). Table 2 shows the computed average RMSE values and differences in TEC (ΔTEC) between GPS TEC, IRI TEC and NN TEC for 2002 at 22h00 UT, 04h00 UT and 10h00 UT. South African Standard Time (SAST) is defined as UT+2 h. The average ΔTEC is defined as:

$$\Delta T_{av} = \frac{1}{N}\sum_{i=1}^{N}\left(T_i - (T_{j=1,2})_i\right) \tag{6}$$

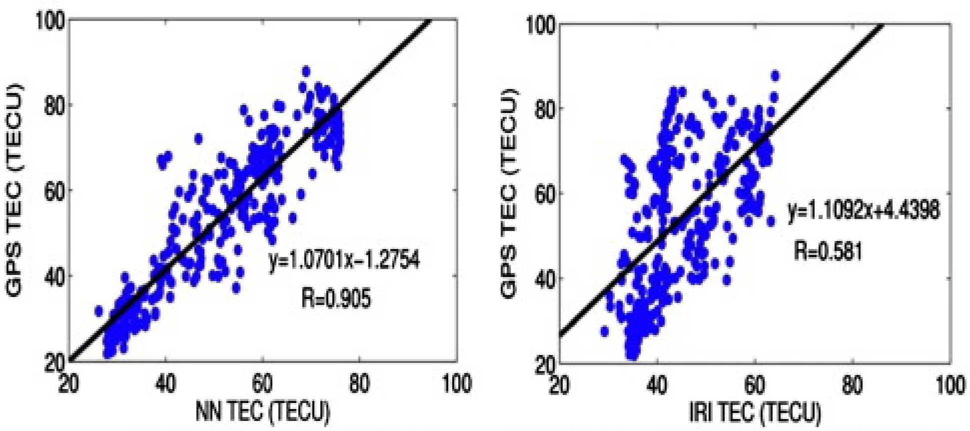
where ΔT_{av} is the average difference between the GPS TEC (T) and NN TEC ($T_{j=1}$) or IRI TEC ($T_{j=2}$), $i = 1, 2, \ldots, N$ and N is the total number of observations at a particular time in 2002.



(a) A plot of GPS TEC versus NN TEC and IRI TEC at 22h00 UT.



(b) A plot of GPS TEC versus NN TEC and IRI TEC at 04h00 UT



(c) A plot of GPS TEC versus NN TEC and IRI TEC at 10h00 UT.

Fig. 4. A scatter plot of GPS TEC versus NN TEC and IRI TEC values over Cape Town (33.95°S, 18.47°E) in 2002 at local midnight, morning sunrise and midday, respectively, showing correlation coefficients obtained from fitted linear regressions.

Table 2.

Average RMSE values and biases between GPS TEC and predicted values (NN TEC and IRI TEC) at different times in 2002 over Cape Town (33.95°S, 18.47°E).

Time (UT)	**RMSE (TECU)**		**Bias (TECU)**	
	NN TEC	**IRI TEC**	**NN TEC**	**IRI TEC**
22h00	3.096	3.768	−1.227	1.207
04h00	3.711	4.023	−1.543	2.553
10h00	7.723	16.825	2.374	9.363

The least bias values or systematic errors of estimation show that the NN model predicts GPS TEC more accurately than the IRI-2001 for the considered particular times. It is however observed that the NN model over predicts GPS TEC during equinoxes in 2002 at 22h00 UT and 04h00 UT.

5.2. Springbok (29.67°S, 17.88°E) and Upington (28.41°S, 21.26°E)

The hourly NN model separately developed for Springbok from the data available for three years (2002, 2003 and 2004) was used to predict GPS TEC for Upington during equinoxes and solstices. The measured GPS TEC values were compared with NN TEC, IRI TEC and ionosonde TEC (ITEC) from a South African ionosonde station located at Louisvale (28.5°S, 21.2°E), as shown in Fig. 5. Although their geographical positions have not been considered so far, the NN optimum architectures at Sutherland Springbok turned out to be identical (Habarulema et al., 2007). With limited data available to develop a fully representative model from a NN application point of view, the NN model predicts correctly the diurnal variations for equinox and solstice days as seen in Fig. 5. Due to the very limited number of GPS data points for June 21 and September 23, winter solstice and spring equinox are represented by June 22 and September 22. Predictions for autumn equinox and summer solstice were obtained for March 19 and January 2 instead of March 21 and December 22 in 2003 because of the unavailability of GPS data.

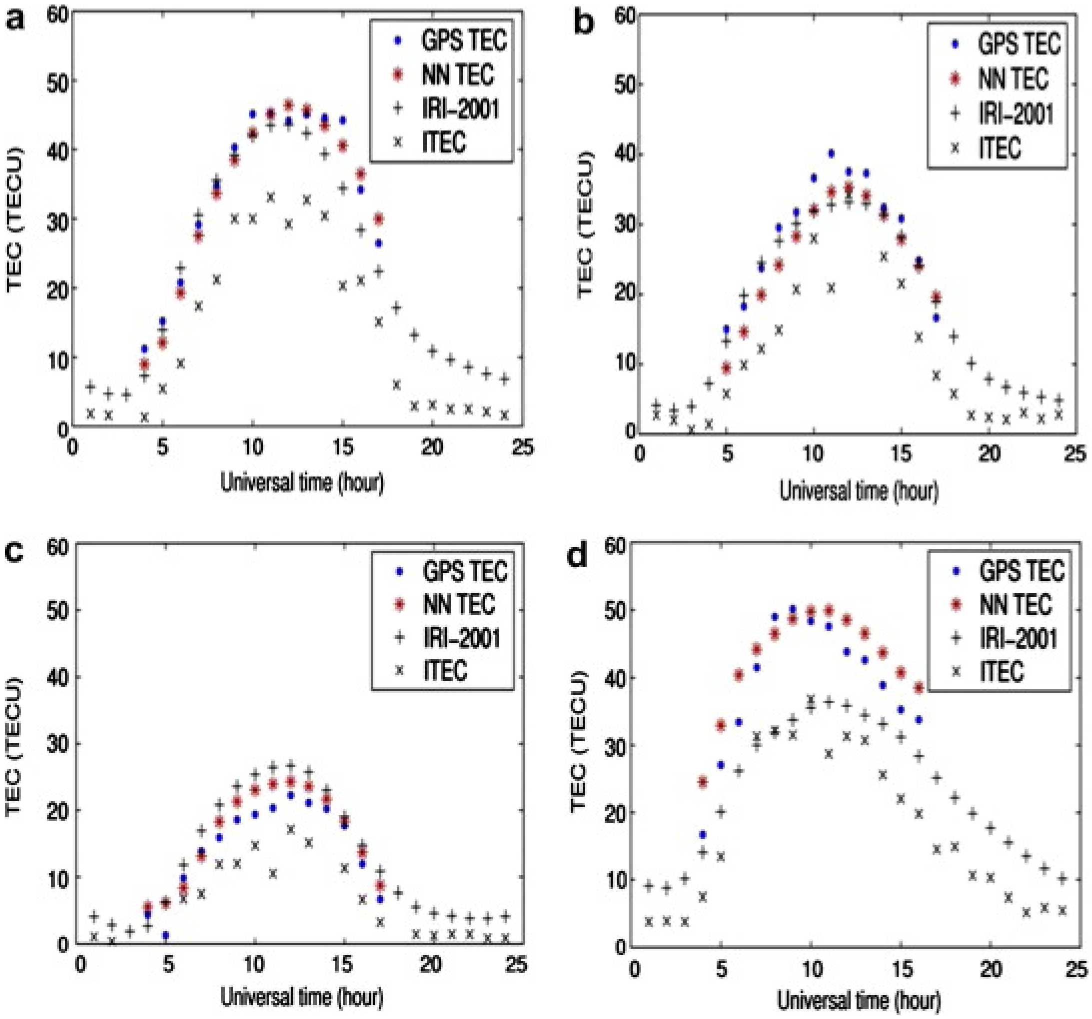


Fig. 5. TEC variations over Upington during equinoxes: (a) March 19, (b) September 22 and solstices: (c) June 22, (d) January 2; all in 2003.

The Louisvale ionograms for equinox and solstice days in 2003 were manually edited using SAO explorer (Reinisch et al., 2004), from which ITEC values were extracted that represent TEC to an altitude of 1000 km. The ITEC is the combination of the measured bottomside and the modelled topside ionosonde profiles. More details about the verification and editing of ionograms obtained from digital pulse sounders can be found in Reinisch et al. (2004). It is observed that the IRI over predicts ITEC as expected for all the four days representing equinoxes and solstices in 2003. This is due to the IRI model estimating TEC values to an altitude of 2000 km (Bilitza, 2001), and a big percentage of TEC being contributed from the topside electron density profile ([Bilitza, 2001] and [Mosert et al., 2007]). Hence the difference between ITEC and IRI TEC is as a result of the IRI topside profile which is an analytical representation of the Bent model ([Bilitza et al., 2006] and [Mosert et al., 2007]). From the available data, the NN predicts GPS TEC more accurately during autumn equinox, while the IRI achieves its maximum prediction during spring equinox. Table 3 shows a summary of coefficients of determination (R^2) between GPS TEC and predicted values (NN TEC and IRI TEC) for the four days representing equinoxes and solstices in 2003 over Upington (28.41°S, 21.26°E) during the periods where data was available. Although there is a difference in the magnitude of TEC values, it is a common observation for both Cape Town and Upington that the IRI over predicts GPS TEC during the winter solstice as shown in Fig. 2(c) and Fig. 5(c). Confirmation of this result requires more analysis since only two locations have been considered. Comparison of Fig. 2 and Fig. 5 shows that TEC is greater in 2002 than in 2003. This may be an illustration of the latitudinal and longitudinal dependence of TEC since there are two different GPS stations under consideration. More importantly, TEC has a strong dependence on solar activity and Fig. 6 shows that 2002 was close to solar maximum while 2003 fell in the declining phase of solar cycle 23.

Table 3.

Coefficients of determination (R^2) between GPS TEC and predicted values (NN TEC and IRI TEC) for the four days representing equinoxes and solstices in 2003 over Upington (28.41°S, 21.26°E).

Month date (in 2003)	**Time (UT) for the available data**	**Coefficient of determination (R^2) between**	
		NN TEC and GPS TEC	**IRI TEC and GPS TEC**
March 19	04h00–17h00	0.9703	0.9287
June 22	04h00–17h00	0.9431	0.9409
September 22	05h00–17h00	0.9211	0.9456
January 2	04h00–16h00	0.9470	0.8452

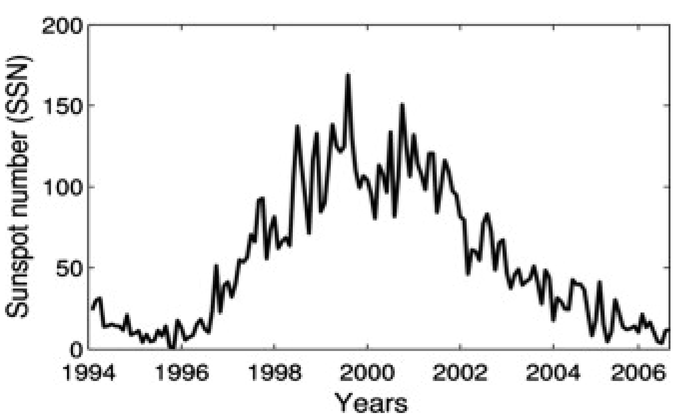
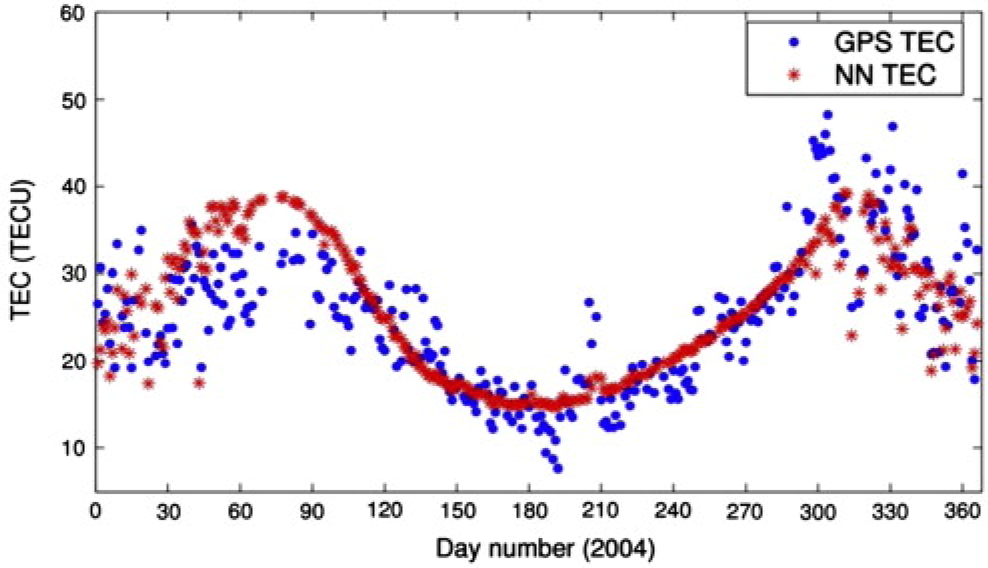


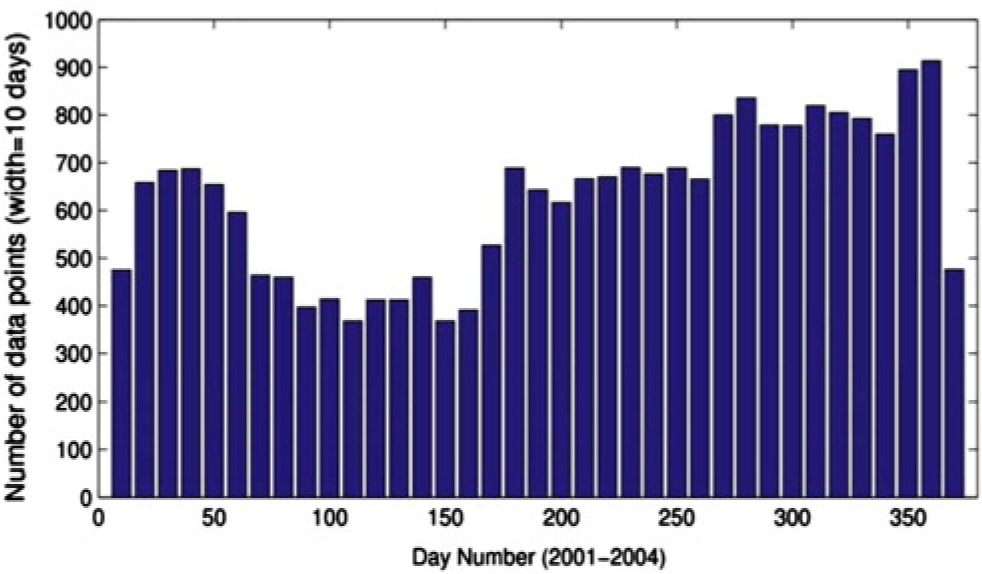
Fig. 6. Monthly averages of sunspot numbers from 1995 to June 2007. Data obtained from http://solarscience.msfc.nasa.gov/.

5.3. Sutherland and Springbok

To complete the network of the selected GPS stations, results from the NN model constructed at Sutherland were used to predict local midday (SAST) TEC values for Springbok in 2004 and results plotted as shown in Fig. 7(a). From this figure, it is clear that the NN over predicts GPS TEC reaching a maximum of ~38 TECU in spring. Four reasons may be put forward to explain this: (1) It could be that TEC varies greatly during equinoxes (Kouris et al., 1999) and thus all parameters which influence TEC have high variation levels during this period, (2) The unavailability of sufficient data for the period used in NN training prohibited a truly representative input space, (3) Inefficient representation of TEC parameters during high solar activity periods and probably at high altitudes in the NN model and (4) Using the NN model developed from Sutherland data to predict TEC at Springbok yet their geographical locations were not included in NN training. Fig. 7(b) is a histogram showing the data points that were used in NN training and validating processes for Sutherland's hourly NN model. There was limited data available during the March equinox compared to other periods and at the moment, this is likely to be the cause of the over prediction. The very low number of data points corresponds to a limited number of all the input parameters which influence TEC during this period. It is a well established concept that a large database is one of the most important requirements in applications involving NN modelling and therefore NNs may not perform well without enough historic data ([Bishop, 1995], [Macpherson et al., 1995], [Williscroft and Poole, 1996], [Conway et al., 1998] and [McKinnell, 2002]). Possibilities of representing TEC variability at high altitudes are still under investigation and will be included in the future updates of the NN model. Although we have used the sunspot number to represent solar activity, the sun follows a cycle of ~11 years (Fig. 6) and with a dataset of at most 5 years included in the NN training, the solar variations may not be effectively predicted at this stage.



(a) TEC variation for Springbok (29.67° S, 17.88° E) at 10h00 UT in 2004 when tested using the NN hourly model results for Sutherland (32.38° S, 20.81° E).



(b) A histogram showing the number of data points used in the NN training during the construction of the hourly model at Sutherland (32.38° S, 20.81° E).

Fig. 7. Comparison of GPS TEC and NN TEC over Springbok at 10h00 UT in 2004 (top figure) and the histogram showing available data used in NN training in the construction of hourly model at Sutherland.

6. Summary, conclusion and future work

In this paper it has been shown that NNs can be used to predict GPS TEC values at locations that were not necessarily included in the NN training within South Africa. A comparison of GPS TEC calculated using the ASHA model with the predictions from the IRI-2001 and NN models over a mid-latitude station located at Cape Town (33.95°S, 18.47°E) was undertaken. Results show that on average the NN predicts GPS TEC more accurately than the IRI-2001 model. The over prediction of GPS TEC by the IRI-2001 model has been observed and this is consistent with the findings of Moeketsi et al. (2007), where a comparison of GPS TEC and IRI TEC over Sutherland (32.38°S, 20.81°E) was completed. This has been attributed to a paucity of Southern Africa ionospheric data included in the IRI model (McKinnell, 2002). A further comparison of GPS TEC with IRI TEC and ITEC revealed that ITEC is less than its counterparts which we expect due to the heights used to determine these three values. ITEC is determined at best to about 1000 km and the accuracy is determined by the derived electron density profile which consists of modelled topside. Therefore it is expected that ITEC will contain some error although we are unable to quantify it at this time. These similar differences between GPS TEC, IRI TEC and ITEC have been reported in other recent sources e.g. (Mosert et al., 2007), (McKinnell et al., 2007) and (Habarulema et al., 2007). Computation of correlation coefficients and systematic errors of estimation showed that results from the NN model are more reliable than the IRI-2001 model over South African locations with reference to GPS TEC prediction. The NN model achieved its maximum prediction accuracy at winter solstice (June 22) and local midday (10h00 UT) in 2002 for Cape Town observations with a RMSE of ∼1.69 TECU and correlation coefficient of 0.905. The confirmation of the NN accuracy in predicting GPS TEC at Cape Town is also reflected in the average systematic errors of estimation as shown in Table 2. On the other hand, the IRI-2001 model predicted GPS TEC more accurately than the NN model at spring equinox with an average RMSE of ∼3.87 TECU (Table 1) and correlation coefficient (R) of ∼0.97 (Table 3) at Cape Town and Upington, respectively. It has not been possible to make concrete conclusions from the GPS TEC predictions obtained over Upington in 2003 due to a very limited database used in the NN training and the incompleteness of the available diurnal GPS data during equinoxes and solstices. It is however observed from the available data that the NN obtains the TEC diurnal shape and the predicted NN TEC shows a strong correlation with GPS TEC. This will be persued in future as more GPS data becomes available. Only five GPS locations out of a total of about 40 possible locations currently present in South Africa have been used in our preliminary studies. Also we have not included the geographical position in our study since it dealt with the development of single station models. Future work will include prediction of GPS TEC calculated by other models, comparing the ASHA model with the IRI at other locations within South Africa, especially at GPS stations that are in close proximity to other ionosonde stations for validation and investigating the latitudinal as well as longitudinal dependence of TEC in NN modelling over the South African GPS receiver stations. This paper forms part of a continuous effort aimed at developing one TEC prediction model for the whole of South Africa.

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