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TEC measurements and modelling over Southern Africa during magnetic storms; a comparative analysis

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ABSTRACT

This paper presents the results from a study designed to investigate the ability of a newly developed neural network (NN) based model to follow total electron content (TEC) dynamics over the Southern African region. The investigation is carried out by comparing results from the NN model with actual TEC data derived from Global Positioning System (GPS) observations and TEC values predicted by the International Reference Ionosphere (IRI-2007) model during magnetic storm periods over Southern Africa. The magnetic storm conditions chosen for the study presented in this paper occurred during the periods 16–21 April 2002, 1–6 October 2002, and 28 October–01 November 2003. A total of six South African GPS stations were used for the validation of the two models during these periods. A statistical analysis of the comparison between the actual TEC behaviour and that predicted by the two models is shown. In addition, ionosonde measurements from the South African Louisvale (28.5°S, 21.2°E) station, located close to one of the validation GPS stations used, are also considered during the Halloween storm period of 28–31 October 2003. The generalisation of TEC behaviour by the NN model is demonstrated by producing predicted TEC maps during magnetic storm periods over South Africa. Presented results demonstrate the ability of NNs in predicting TEC variability over South Africa during magnetically disturbed conditions, and highlight areas for improvement.

1. Introduction

Ionospheric total electron content (TEC) is a highly non-linear physical quantity that has been extensively studied and modelled for a wide range of applications such as geodesy, communication, surveying, space weather dynamics and error correction in relation to Global Navigation Satellite Systems (GNSS) applications (e.g. Hofmann-Wellenhof et al., 1992; Misra and Enge, 2006). Among other factors that play an important role in TEC variability are solar activity changes, geomagnetic activity fluctuations, seasonal and diurnal variations, and the geographic location where instruments responsible for its measurements are situated (Hofmann-Wellenhof et al., 1992). During magnetic storms, the ionospheric electron density response is mainly characterised by positive and negative storm phases depending on many conditions including latitude, season and storm intensities. At times both phases exist during the same storm period and these sudden changes make it difficult to accurately predict TEC variability. In South Africa, an attempt has been made to develop a National neural network (NN) model that can be used to predict TEC values as a function of parameters that influence TEC variability. This paper describes a statistical comparison of predicted TEC from the NN model and the International Reference Ionosphere (IRI) with Global Positioning System (GPS) derived TEC over South Africa during magnetic storms. The scope of this paper is constrained to the validation of the developed NN TEC model during magnetic storms and the reader is referred to Opperman et al. (2007) for details on the algorithm used to derive the TEC values from GPS measurements, and Habarulema et al. (2007, 2009c) for a description of the developed NN based model used to predict GPS-derived TEC variations over Southern Africa. The results presented in this paper are obtained from the validation of the National NN model developed using data from 10 stations distributed throughout South Africa (as shown in Fig. 1) and used to predict TEC variability over Pietermaritzburg, PMBG (29.60°S, 30.38°E), Middleburg, MRBG (25.77°S, 29.45°E), Upington, UPTN (28.41°S, 21.26°E), and Sutherland, SUTH (32.38°S, 20.81°E), during the Halloween storm of 28 October to 1 November 2003; and Cape Town, CPTN (33.95°S, 18.47°E), and Kimberley, KLEY (28.74°S, 24.81°E), during 16–21 April and

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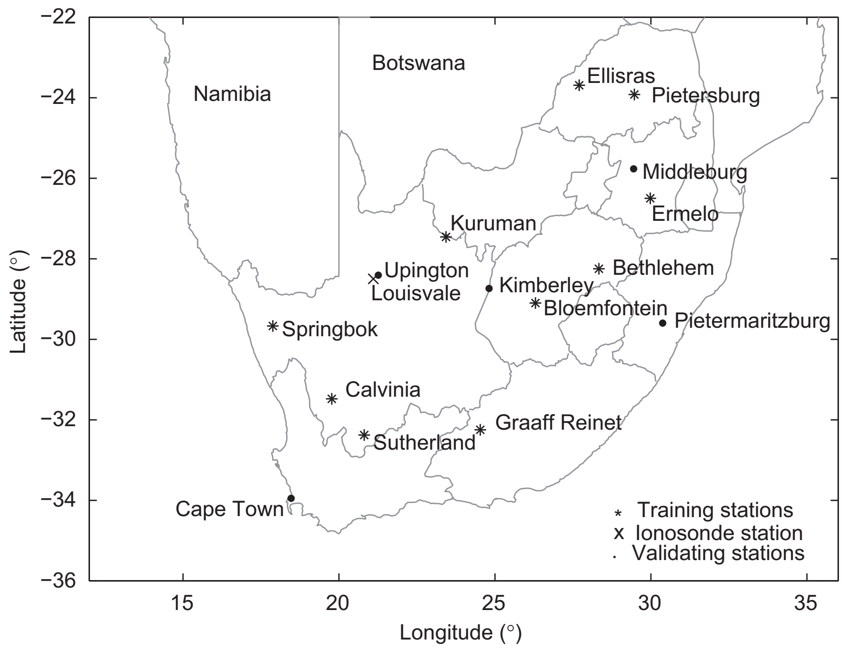

Fig. 1. A South African map showing the GPS receiver and ionosonde stations used in this study.

1–6 October, 2002 storms. In all cases, our results were compared with the latest version of the IRI model (IRI-2007) using the standard options. The NN model was developed to predict vertical TEC and all values are expressed in TEC units (TECU) where 1 TECU is equivalent to $1 \times 10^{16}\,ele/m^2$. The validation outcome(s) provides an indication of the required improvements and the level of our efforts in modelling the TEC parameter during magnetically disturbed periods which are not easily predictable. Fig. 1 shows a South African map depicting the GPS receiver stations used in the NN model's development and validation during this study. The Louisvale ionosonde station (which is used for validation) is also indicated on the map. The geomagnetic storms considered were classified using the disturbance storm time (Dst) index data which was downloaded from the coordinated data analysis web (http://cdaweb.gsfc.nasa.gov/cdaweb/sp_phys/).

2. TEC studies and modelling in South Africa

The characterisation of the ionosphere using GPS derived TEC measurements is a relatively new field of study in South Africa. Within South Africa, GPS data are playing a role as a supplement to ionosonde data from four ionosonde stations; Grahamstown (33.30°S, 26.53°E), Madimbo (22.4°S, 30.9°E), Louisvale (28.5°S, 21.2°E), and Hermanus (34.4°S, 19.2°E). Cilliers et al. (2004) presented first results of electron density profiles obtained by tomographically reconstructing TEC from the South African GPS receiver network. Moeketsi et al. (2007) adapted the University of New Brunswick (UNB) ionospheric mapping technique for the Southern Africa region to characterise solar cycle effects on GNSS derived ionospheric TEC over Southern Africa. Opperman et al. (2007) developed an algorithm to estimate TEC values from GPS observations over South Africa based on the global spherical harmonic algorithm (Schaer, 1999) and McKinnell et al. (2007) did a comparison of TEC derived from GPS and ionosonde data to compute the plasmaspheric content over Grahamstown (33.30°S, 26.53°E), which was the first South African location to have an ionosonde collocated with a GPS receiver. The first feasibility study into TEC prediction/modelling over South Africa using the NN technique was carried out by Habarulema et al. (2007) using GPS data from single stations. This work has been expanded to include more GPS receivers in an effort to develop a TEC prediction model for South Africa (Habarulema et al., 2009c). In these predictions, multiple inputs to the NN were used and the NN models have been found to be relatively efficient in reproducing TEC patterns during quiet conditions. The TEC values determined using the adjusted spherical harmonic analysis (ASHA) algorithm are used together with factors that are known to influence TEC (diurnal and seasonal variations, solar and magnetic activities and geographical position) to construct a NN model that can be used to predict TEC variations over different locations within South Africa. In this work, the National NN model which is a GPS-based TEC prediction model that was developed from a combination of GPS TEC data from 10 stations distributed all over South Africa (Habarulema et al., 2009c) has been used in an attempt to characterise TEC dynamics during geomagnetic storms. The model made use of data at a time resolution of 1 min over an interval of 5 years (2000–2004) and can therefore generate predictions within this time interval. TEC values derived from Louisvale ionosonde measurements are also compared with values from the NN TEC model and GPS TEC during the Halloween storms of 28 October to 1 November 2003. The electron density profiles obtained from ionosonde measurements can be used to derive the ionosonde TEC (ITEC) up to an altitude of about 1000 km. This is achieved by a combination of the measured bottomside and modelled topside ionospheric profiles obtained from the ARTIST4 scaling software used within the digisonde systems (Reinisch et al., 2004). On the other hand, TEC predictions over Southern Africa can be generated by the IRI which is a global model that provides monthly median values of TEC (among other ionospheric parameters) at any location over the entire globe (Bilitza, 2001). IRI currently contains a geomagnetic activity dependence option based on the time empirical ionospheric correction model (STORM) (Araujo-Pradere et al., 2002; Araujo-Pradere and Fuller-Rowell, 2002; Bilitza, 2003) which was formulated out of a study of the consistent and repeatable storm-time ionospheric response characteristics. The STORM model design includes seasonal dependence in the migration of