AfriTEC: A neural network based model of the African regional ionospheric Total Electron Content

Daniel Okoh

International Workshop on Machine Learning for Space Weather
Buenos Aires - Argentina
7 – 11 November, 2022

Outline

Introduction

Data & Methods

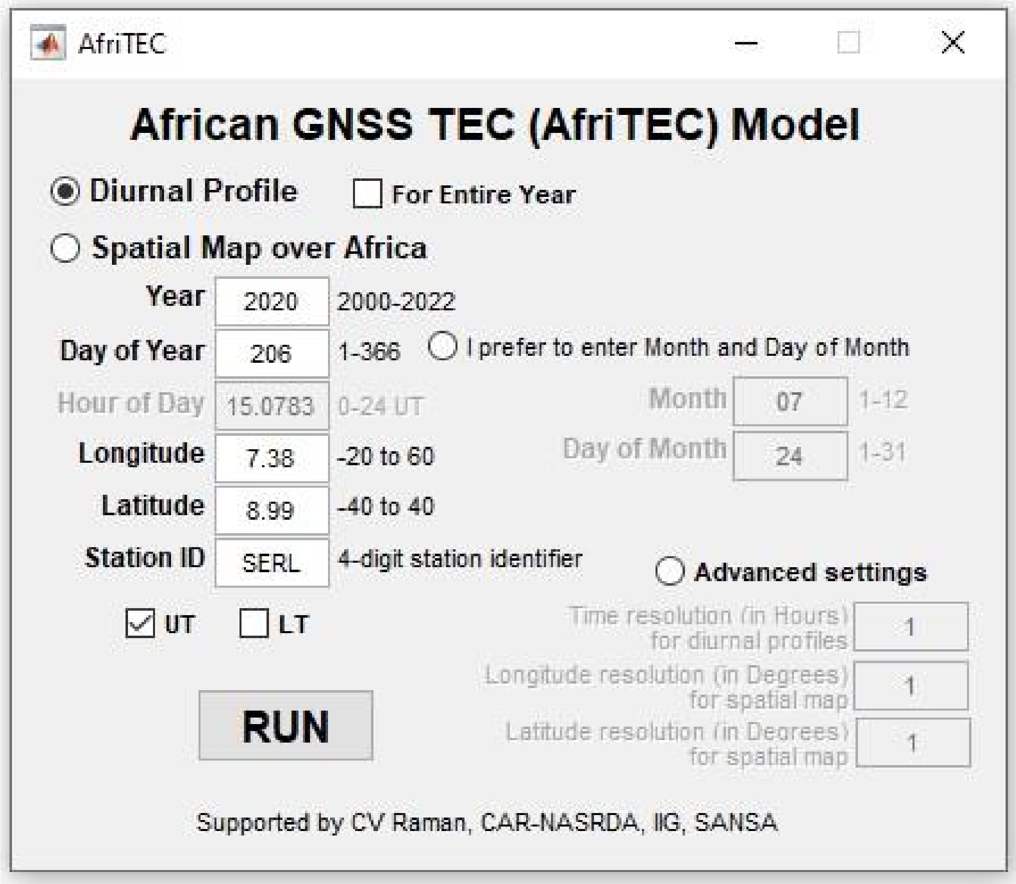
Results & Discussion

Global 3D-NN Model

Introduction

AfriTEC is acronym for:
African regional ionospheric Total Electron Content. It is a model of the ionosphere over the entire African region.

Motivation for developing the AfriTEC is based on the fact that the African region is least studied. This is obviously due to paucity of data available from the region.



Introduction

Quiet time

JGR Space Physics

RESEARCH ARTICLE
10.1029/2019JA027065

A Neural Network-Based Ionospheric Model Over Africa From Constellation Observing System for Meteorology, Ionosphere, and Climate and Ground Global Positioning System Observations

Daniel Okoh[1,2], Gopi Seemala[2], Babatunde Rabiu[1], John Bosco Habarulema[3,4], Shuanggen Jin[5,6], Kazuo Shiokawa[7], Yuichi Otsuka[7], Malini Aggarwal[2], Jean Uwamahoro[8], Patrick Mungufeni[9], Bolaji Segun[10], Aderonke Obafaye[1], Nada Ellahony[11], Chinelo Okonkwo[12], Mpho Tshisaphungo[3], and Dadaso Shetti[13]

Key Points:
- The first regional TEC model over the entire African region using empirical observations is developed
- The model offers opportunities to conduct high spatial resolution investigations over the African region
- EIA occurrence is reduced during the June solstice, and the anomaly

Storm time

Space Weather

RESEARCH ARTICLE
10.1029/2020SW002525

Storm-Time Modeling of the African Regional Ionospheric Total Electron Content Using Artificial Neural Networks

Daniel Okoh[1,2,3], John Bosco Habarulema[2,4], Babatunde Rabiu[1,3], Gopi Seemala[5], Joshua Benjamin Wisdom[6], Joseph Olwendo[7], Olivier Obrou[8], and Tshimangadzo Merline Matamba[2]

Key Points:
- First report on storm-time modeling of TEC across the entire African region is presented
- Inclusion of time history of geomagnetic activity indicators improved TEC modeling by about

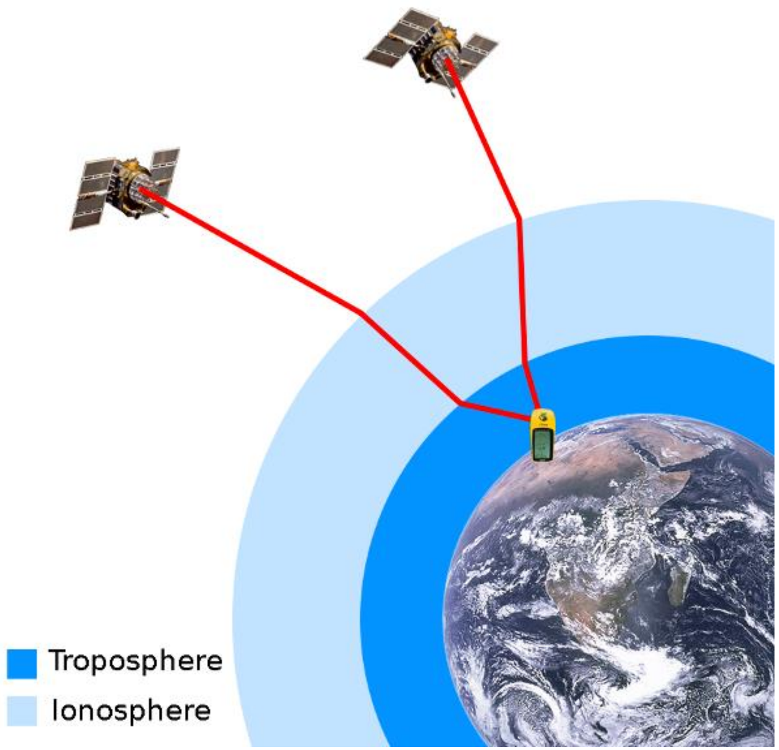
Introduction

The explosion in number of GNSS receivers, and their rapidly growing applications, triggered the interest to develop the model.

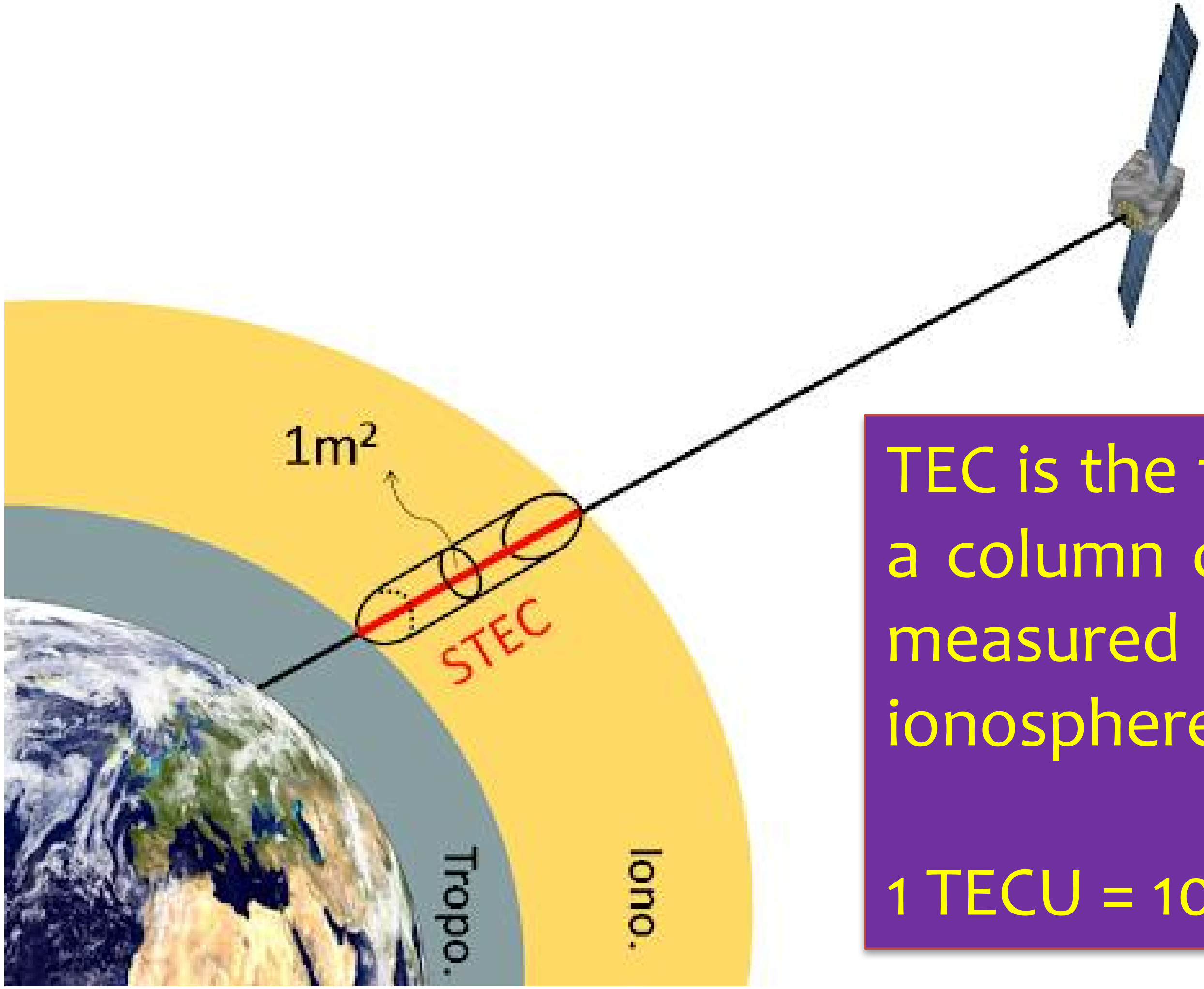
The ionosphere is the major source of error for GNSS systems.

GNSS radio signals are delayed when they propagate through the ionosphere.

The delay translates to a quantity known as TEC (Total Electron Content), which in turn can be applied to correct the errors introduced by the ionosphere, especially for single frequency receivers.



Introduction



TEC is the total number of electrons in a column of unit cross sectional area, measured from top to bottom of the ionosphere.

1 TECU = 10^{16} electrons/m^2

Data & Methods

Data used in this work include:

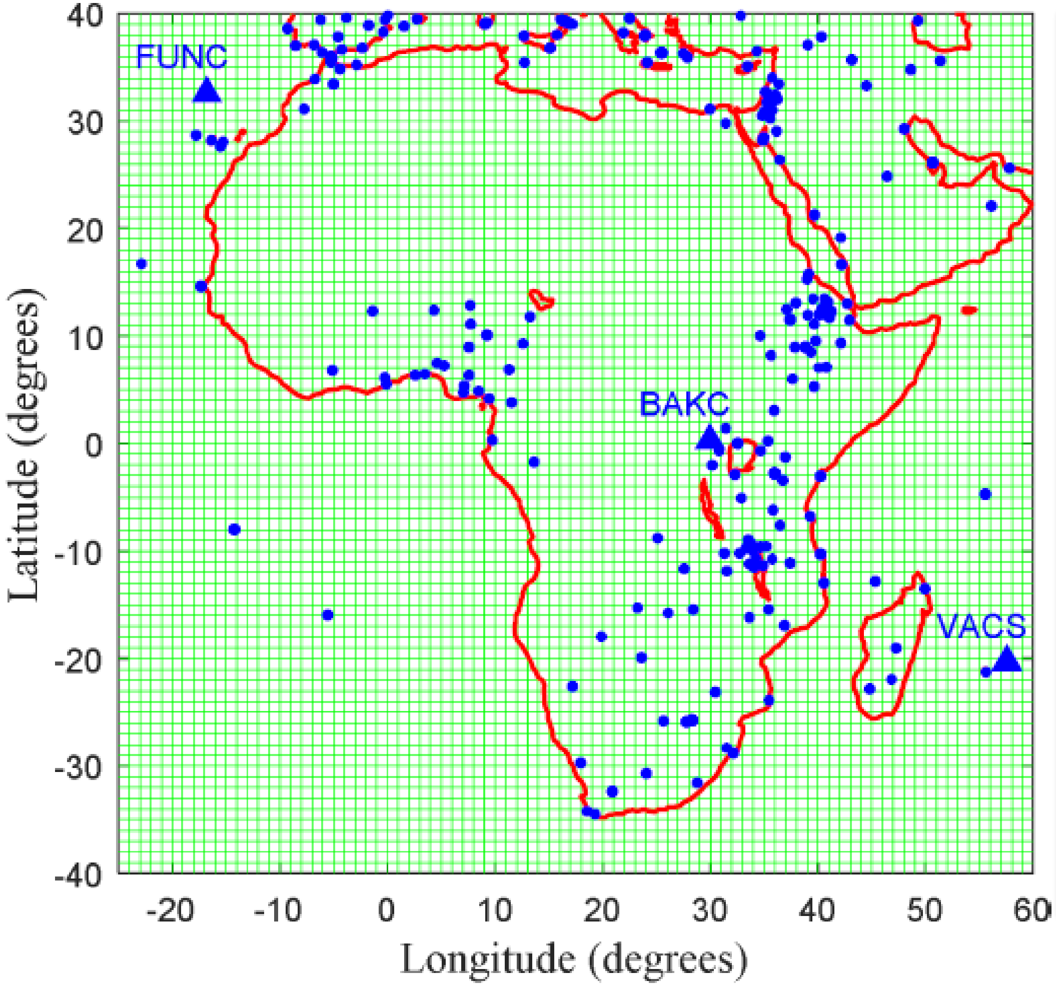
- GNSS data from ground based receivers
- GNSS data from satellite based receivers (COSMIC Radio Occultation (RO))
- Indices for solar and geomagnetic activities
- Data from other ionospheric models (IRI-Plas, NeQuick, and GIM (Global Ionospheric Maps))

Data & Methods

Ground based GNSS Data used in this work was obtained from the following sources:

- The African Geodetic Reference Frame (AFREF, http://afrefdata.org)
- The Nigeria GNSS Reference Network (NIGNET, www.nignet.net)
- The South African network of continuously operating GNSS base stations (TRIGNET, http://www.trignet.co.za)
- The University of California, San Diego, SOPAC & CSRC GARNER GPS Archive (ftp://garner.ucsd.edu)
- The National Aeronautics and Space Administration's CDDIS Archive of GNSS products (ftp://cddis.gsfc.nasa.gov)
- The Global Data Center of the International GNSS Service (ftp://igs.ensg.ign.fr)
- The UNAVCO Archive of GNSS Data (ftp://data-out.unavco.org)
- The Geodetic Data Archiving Facility (ftp://geodaf.mt.asi.it)

Data & Methods

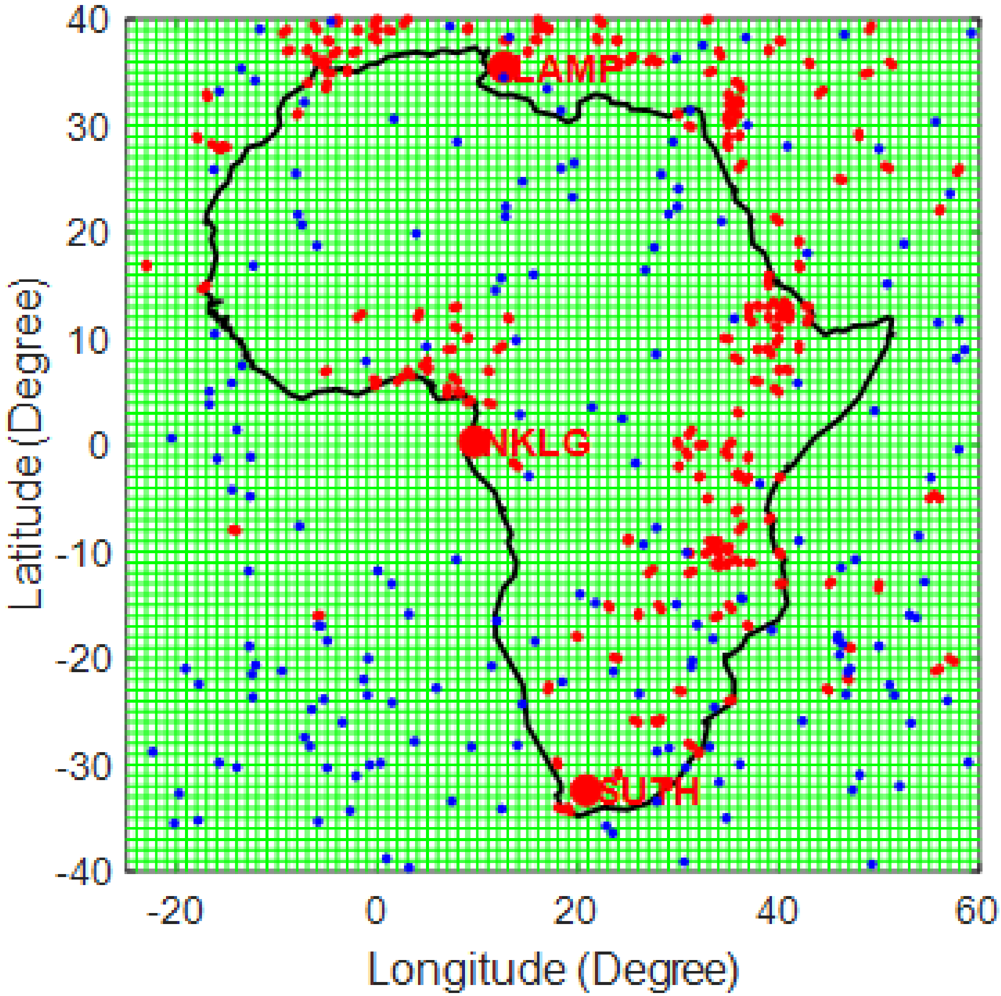


Map of Africa showing locations of ground based GNSS receivers used in this work.

Stations marked in triangles (and labeled using the 4-digit station codes) were used for testing the spatial performance of the networks.

The green background lines show 1° × 1° grids of longitude and latitude used to bin the final observations.

Data & Methods

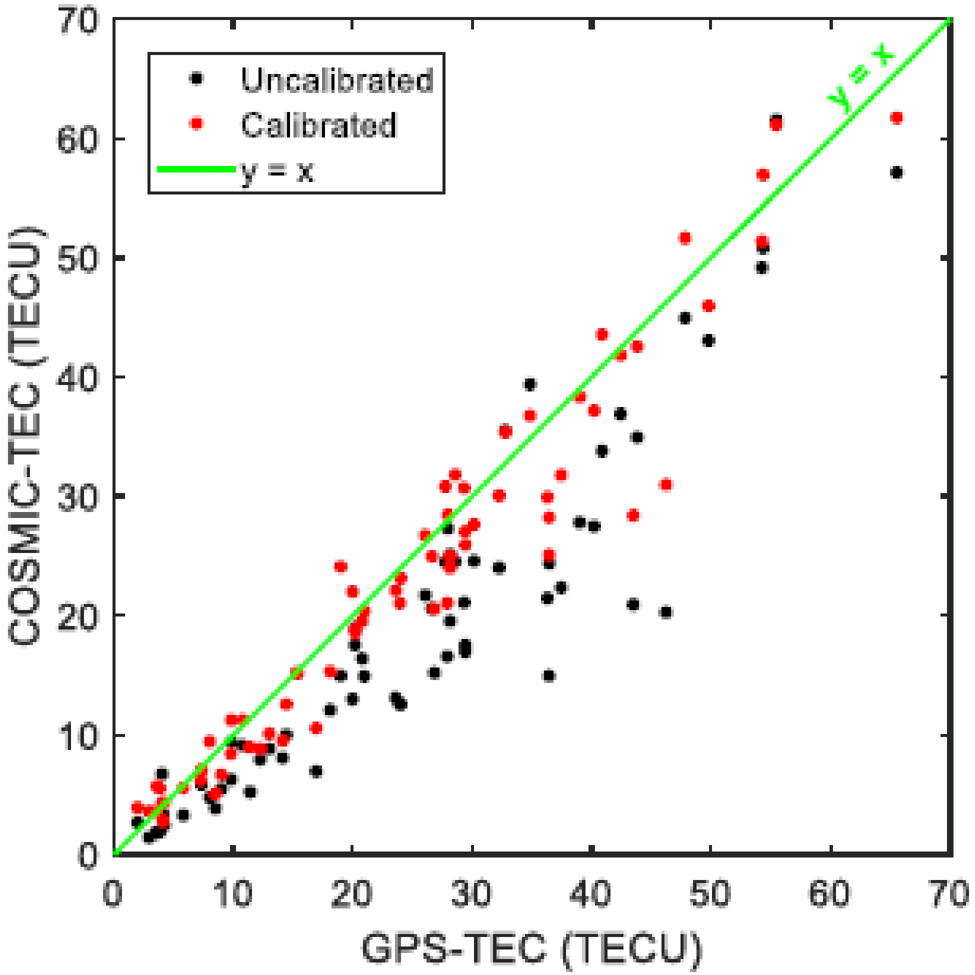


Configuration for storm time model:

Red dots: Ground based GNSS receivers.

Blue dots: COSMIC data footprints (locations of maximum electron densities in various RO events) during the storm period of 7-9 March 2012.

Data & Methods



Calibration of COSMIC Data:

This was necessary considering the disparity between the datasets, especially with regards to the upper integration limit.

GPS: ~20,200 km
COSMIC: ~800 km

An illustration of how the calibrated and un-calibrated COSMIC-TECs compare with ground GPS-TEC at the 1° × 1° grid cell of NKLG station

Data & Methods

- Total number of GNSS receiver stations: 269
- Years: 2000 to 2018

- Gopi GPS-TEC analysis application software used for RINEX to TEC Processing
- Hourly averaging
- 30° elevation cut-off for multipath error minimization

Data & Methods

- SSN data was obtained from the WDC-SILSO, Royal Observatory of Belgium, Brussels (website: http://www.sidc.be/silso/datafiles).
- F10.7 data was obtained from the National Oceanic and Atmospheric Administration, NOAA (ftp://ftp.ngdc.noaa.gov/STP/space-weather/solar-data/solar-features/solar-radio/noontime-flux/penticton/penticton_observed/listings/).
- Solar UV flux data was obtained from the University of South California Dornsife (https://dornsifecms.usc.edu/space-sciences-center/download-sem-data).
- Dst and Kp indices were obtained from NASA’s OMNIWeb (https://omniweb.sci.gsfc.nasa.gov/form/dx1.html).

For quiet model: |Dst|<=20 nT

For storm model: |Dst|>=50 nT or Kp>=4

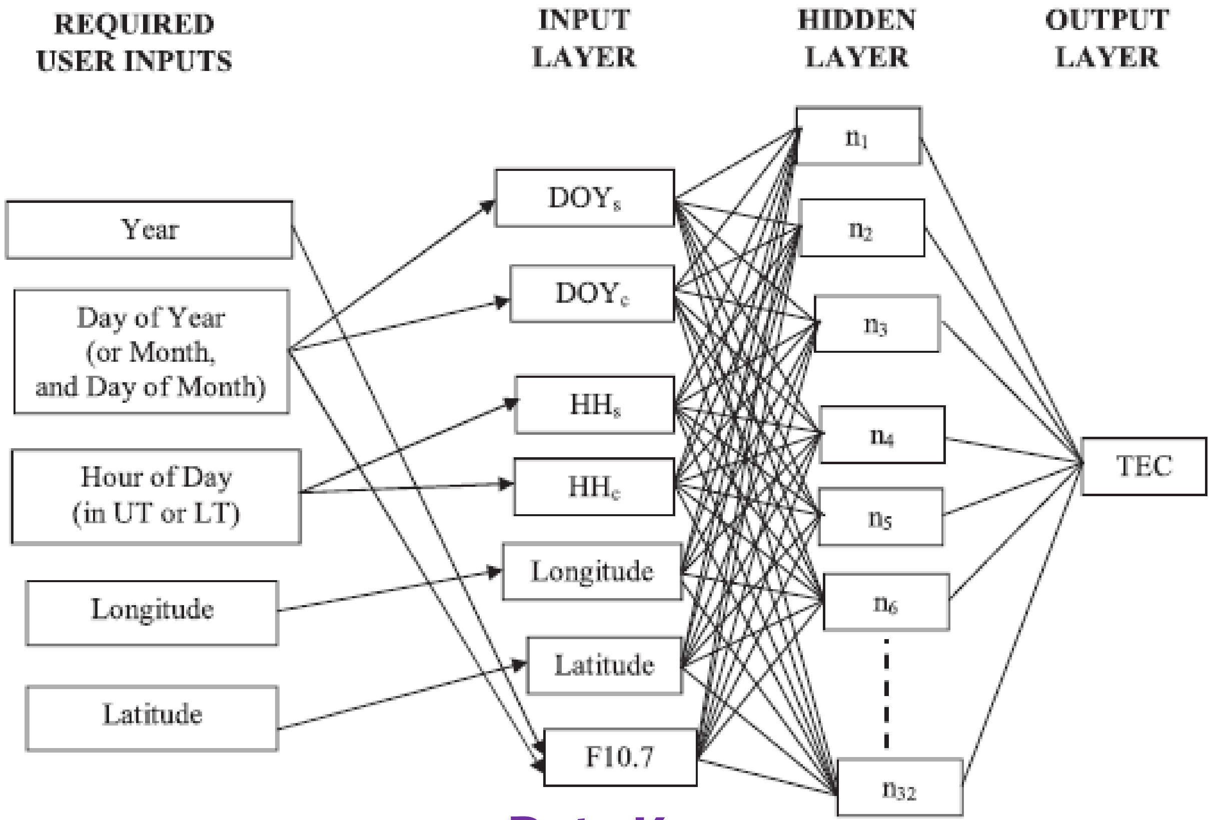
Data & Methods

Computer neural networks were used

- They are a system of information processing techniques inspired by the manner in which the human brain works; they can learn trends and patterns in data and consequently be able to predict future trends in the data. For this reason, they are hugely applied in predictive modeling .

- Strengths and advantages: Ability to represent both linear and non-linear relationships directly from the data being modeled.
- Previous regional efforts: Habarulema et al., 2009; Habarulema, 2010; Okoh et. al, 2016

Data & Methods



Dst Kp

d/dt(Dst) d/dt(Kp)

$$DOY_s = \sin\left(\frac{2\pi \times DOY}{365.25}\right) \qquad DOY_c = \cos\left(\frac{2\pi \times DOY}{365.25}\right),$$

$$HH_s = \sin\left(\frac{2\pi \times HH}{24}\right) \qquad HH_c = \cos\left(\frac{2\pi \times HH}{24}\right),$$

$$LT = UT + Long/15,$$

Sample architecture of the neural network model implemented in this work

Data & Methods

$$H_m = \tanh(I_{wm} \times I_m + B_1)$$

$$O_m = \tanh(H_{wm} \times H_m + B_2)$$

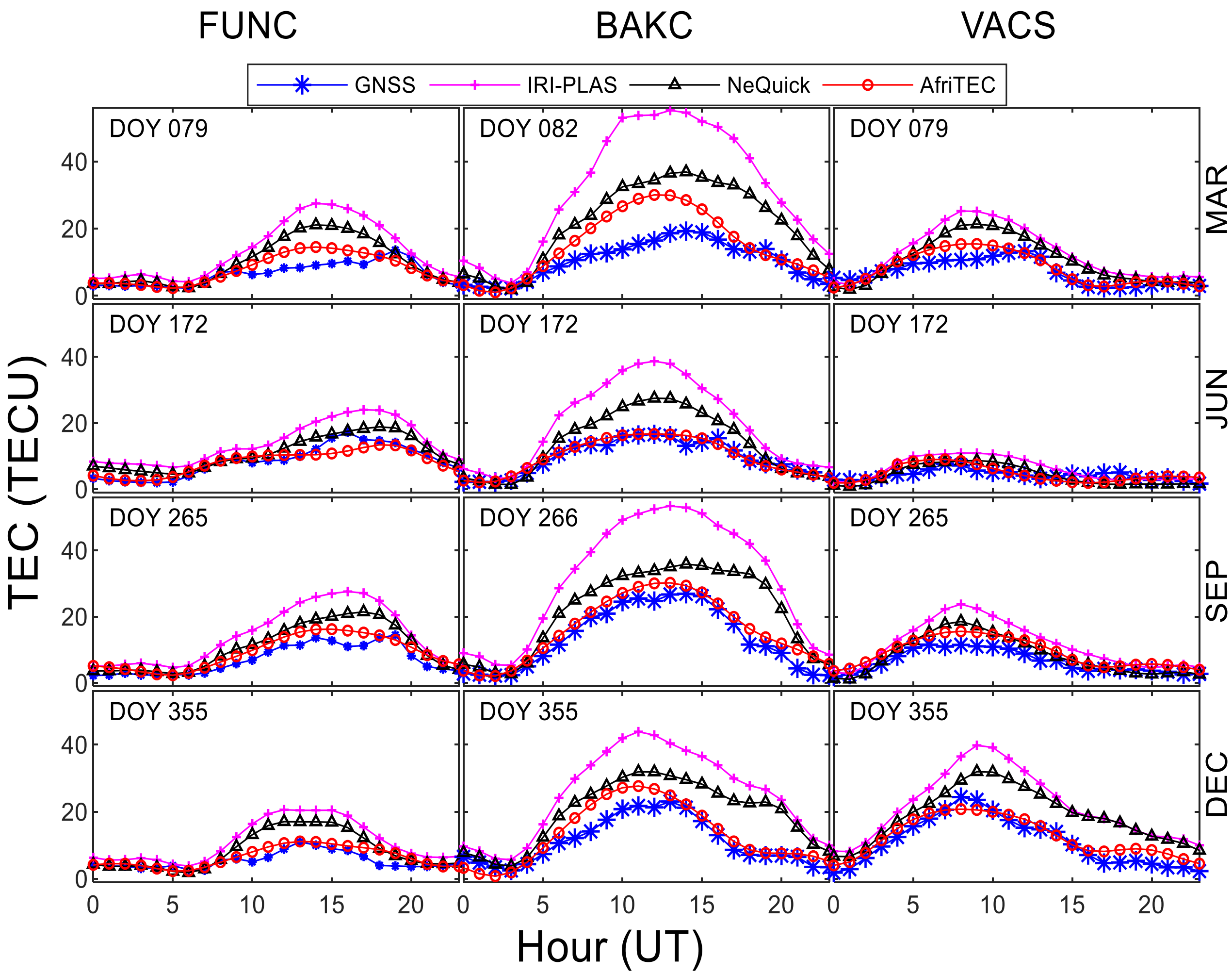
The hyperbolic tangent function is intentionally used as transfer function between the hidden and output layer so as to provide a boundary for the TEC output which should not be negative by physical definition.

I_m, H_m, and O_m are respectively variable matrices for the input, hidden, and output layers.

I_{wm} and H_{wm} are respectively weight matrices for the input and hidden layers.

B_1 and B_2 are the bias vectors.

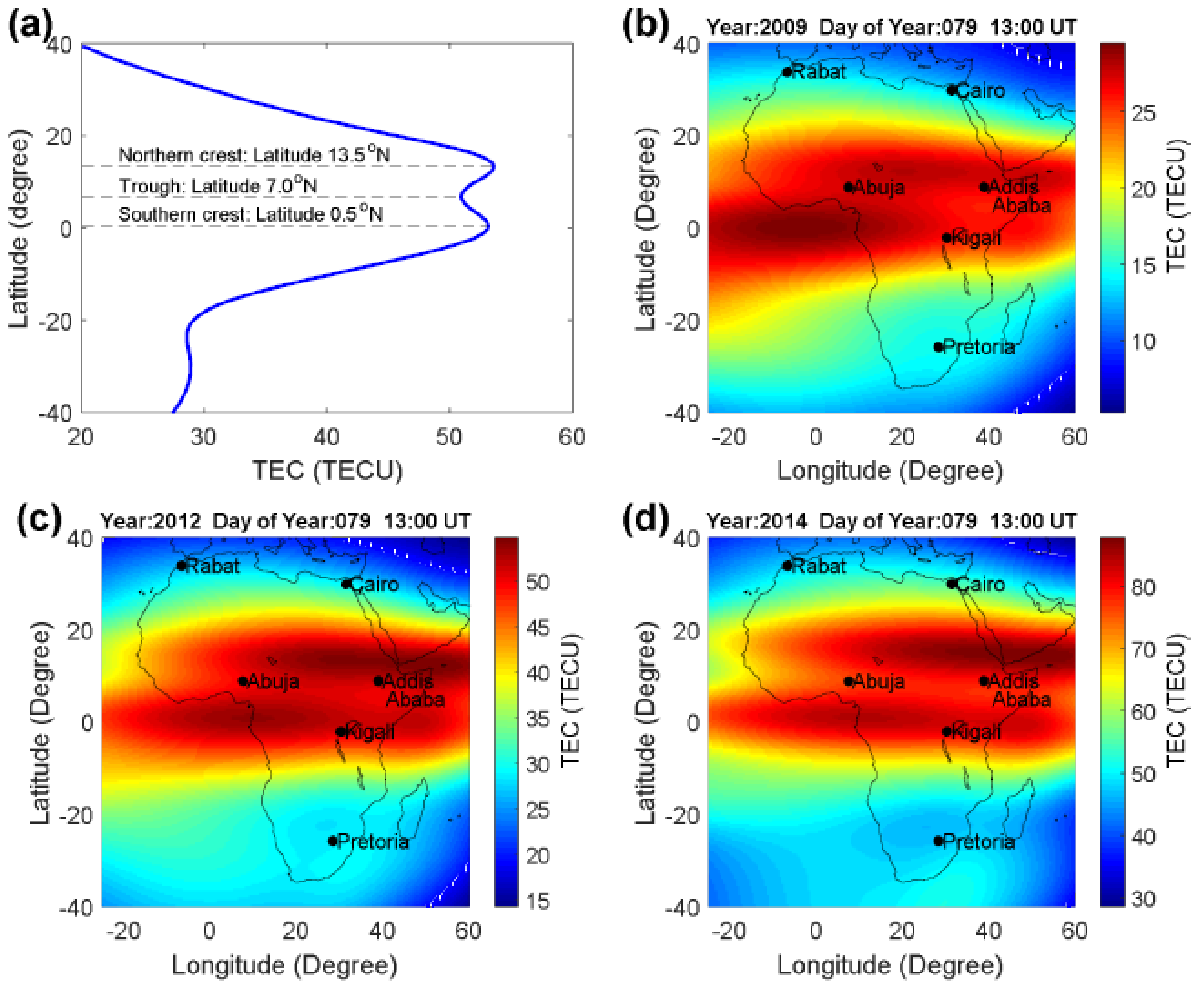
Results & Discussions



With reference to GPS-TEC (2009);

AfriTEC RMSE = 3.76 TECU
NeQuick = 6.65 TECU
IRI-Plas = 10.44 TECU

Results & Discussions



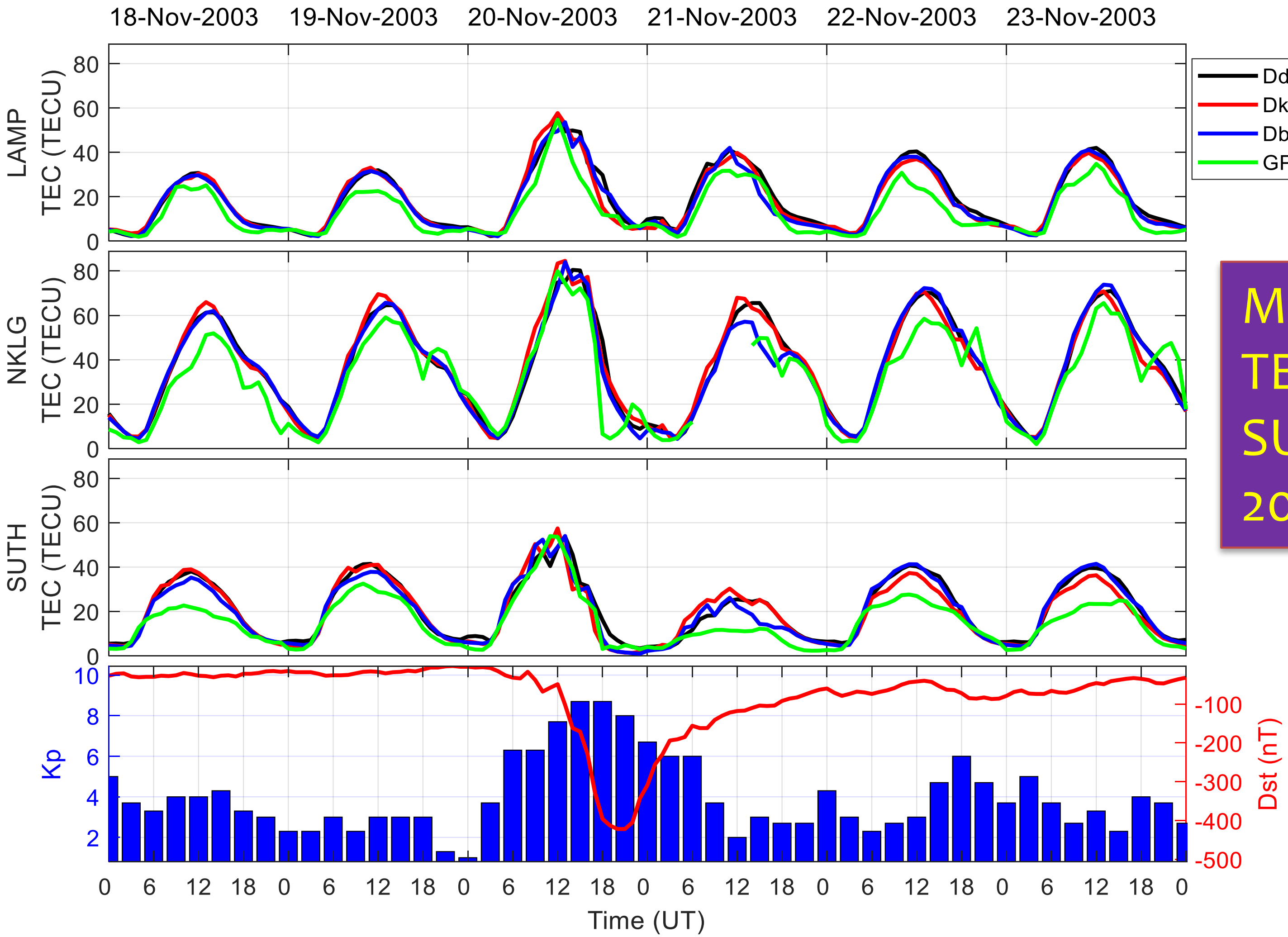
Separation between crests increase with increasing level of solar activity

- Maximum during December solstice

Table 1
Latitudinal Locations of the Equatorial Anomaly Crests and Troughs Measured Along the Meridian of Longitude 20°E

Season/Year	Latitude of northern crest (±0.5°)	Latitude of trough (±0.5°)	Latitude of southern crest (±0.5°)	Latitudinal separation between crests (±1.0°)
Classification by seasons of year 2012				
March equinox (F10.7 = 101)	13.5	7.0	0.5	13.0
September equinox (F10.7 = 125)	15.0	6.5	1.0	14.0
December solstice (F10.7 = 111)	13.5	5.5	−2.5	16.0
Classification by years of varying solar activity during March equinoxes				
2009 (F10.7 = 68)	12.0	6.0	0.5	11.5
2012 (F10.7 = 101)	13.5	7.0	0.5	13.0
2014 (F10.7 = 150)	15.5	7.5	0.5	15.0

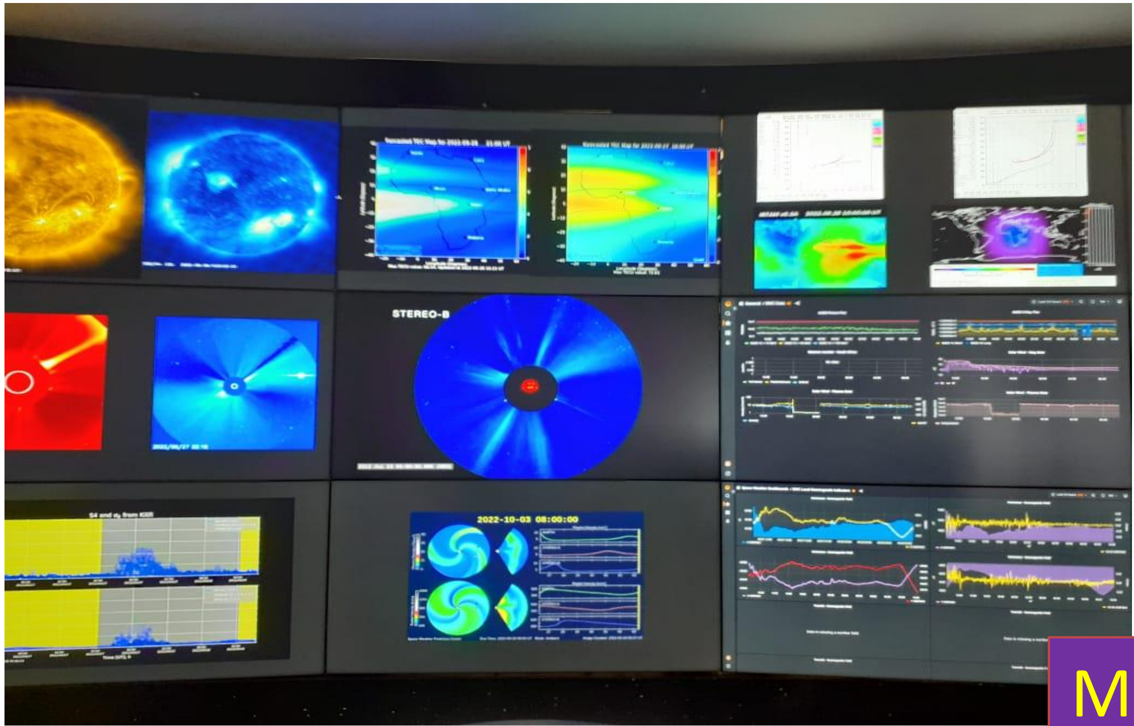
Results & Discussions



Modeled TECs versus GPS TECs at LAMP, NKLG, and SUTH, during the storm of 20 November 2003.

Results & Discussions

AfriTEC is for real-world applications:



Centre for Atmospheric Research
(http://carnasrda.com/tec_models)

MATLAB Central website
(https://www.mathworks.com/matlabcentral/fileexchange/69257-african-gnss-tec-afritec-model?s_tid=prof_contriblnk)

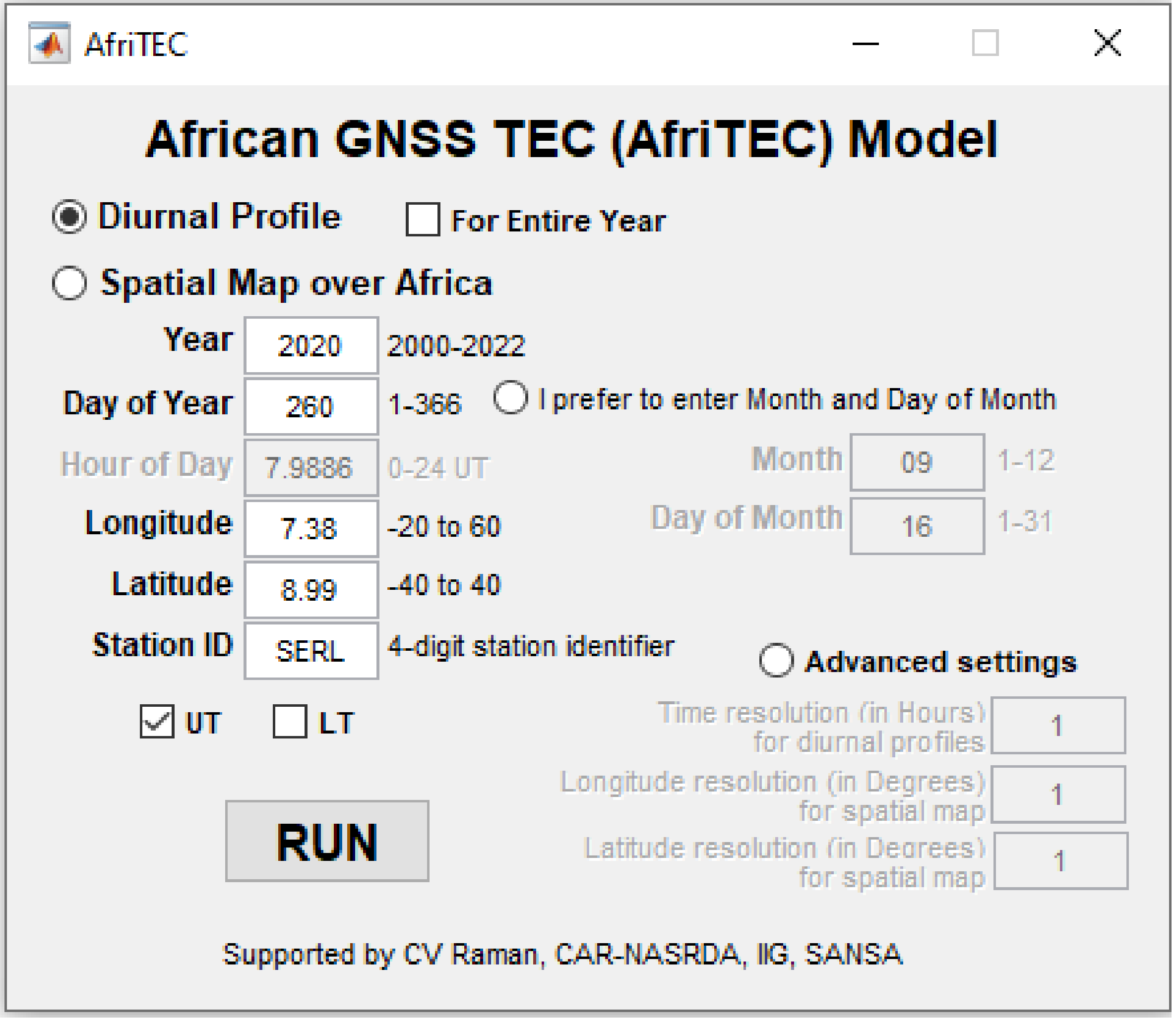
SANSA Space Weather Centre
South African National Space Agency, Hermanus

Results & Discussions

User Interface

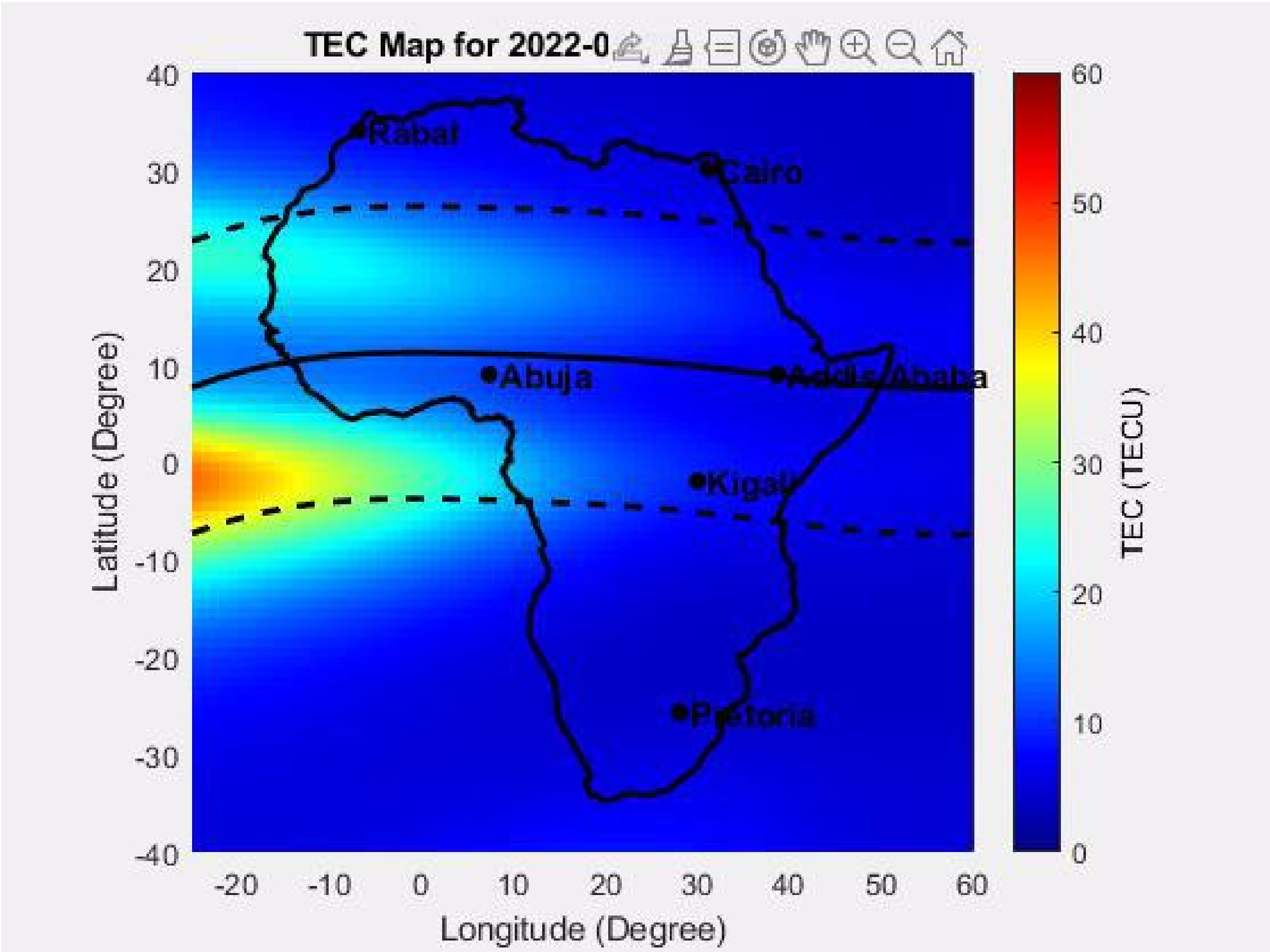
For user friendliness, a graphical user interface is developed.

Detailed information on how to use the AfriTEC model is given on the model web pages

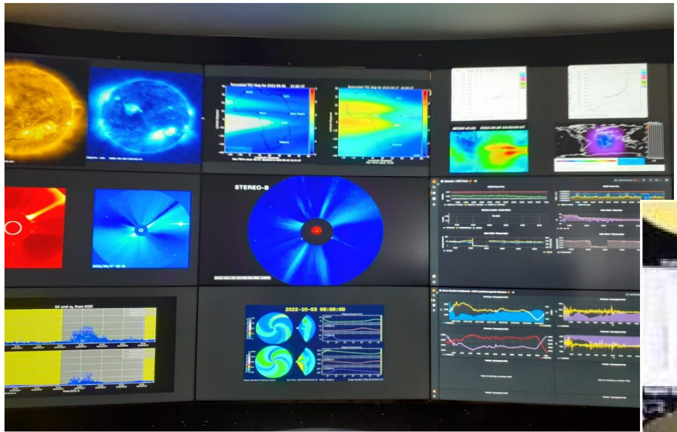


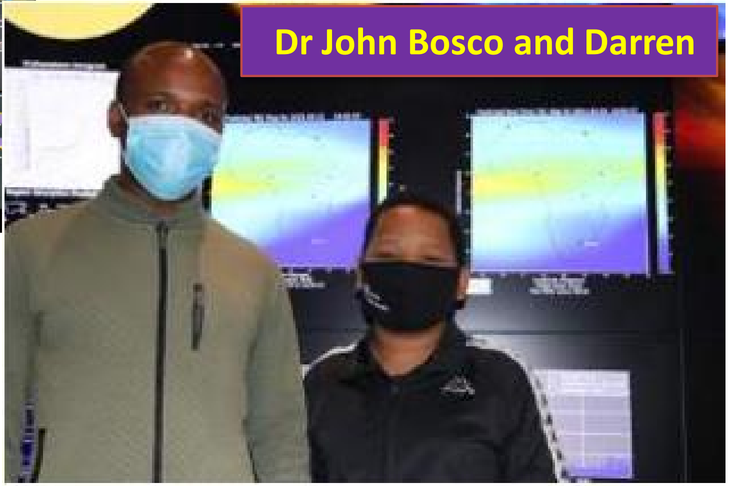
Results & Discussions

AfriTEC Prediction for Today: 10 Nov. 2022



Results & Discussions





Dr John Bosco and Darren

“The product, called AfriTEC, was defined as a priority for development within the domain of navigation applications impacted by space weather, and has now been completed. It will be included in the range of products and services offered as part of the 24-hour Regional Space Weather Centre. AfriTEC will allow clients to estimate the delay on GPS satellites and will serve as a basis for estimating frequencies for HF communications”

Independent Evaluations/Validations

Performance Analysis of Ionospheric TECmodelsoverthe Africanregion during the geomagnetic storm of March 2015

de Dieu Nibigira Jean
University of Alberta Faculty of Education
VENKATA RATNAM DEVANABOYINA (ratnam2002v@gmail.com)
KL University https://orcid.org/0000-0002-2389-4196
sivakrishna kondaveeti
Malla Reddy University

"AfriTEC, which is a regional model, recorded lowest RMSE values over all the stations. The prediction results show that the regional model performance is better than the global ionospheric models (IRI-2016 and Nequick-G models) especially over EIA latitudes of African region".

S.No.	IGS Station Code	Geographic/ Geomagnetic latitude (degree)	Geographic/ Geomagnetic longitude (degree)	GNSS constellations
1	NOT1	36.876N/39.24N	14.990E/80.01E	GPS + GLO + GAL + BDS + SBAS
2	SFER	36.464N/38.50N	6.206W/79.81E	GPS + GLO + GAL + SBAS
3	MAS1	27.764N/29.83N	5.633W/77.73E	GPS + GLO + GAL + BDS + SBAS
4	CPVG	16.732N/18.91N	2.935W/75.57E	GPS + GLO + GAL + BDS + SBAS
5	BJCO	6.385N/9.18N	2.450E/73.88E	GPS + GLO
6	NKLG	0.354N/3.39N	9.672E/72.93E	GPS + GLO + GAL + BDS + SBAS + IRNSS
7	MBAR	0.601S/2.97N	30.738E/72.86E	GPS + GLO + GAL + BDS + IRNSS
8	MAYG	12.782S/10.39S	45.258E/70.67E	GPS + GLO + GAL + BDS + SBAS + IRNSS
9	HARB	25.887S/22.96S	27.707E/68.43E	GPS + GLO + GAL + BDS + SBAS + IRNSS
10	SBOK	29.669S/26.51S	17.879E/67.72E	GPS

Independent Evaluations/Validations

Space Weather

RESEARCH ARTICLE
10.1029/2021SW003013

Development and Evaluation of Near-Real Time TEC and Ancillary Products for SANSA Space Weather

Tshimangadzo M. Matamba[1] and Donald W. Danskin[1]

[1]South African National Space Agency (SANSA), Hermanus, South Africa

Key Points:

- Maps of Total Electron Content, spatial and temporal gradients over the South African Region
- Root mean squared error (RMSE) and quality factors introduced to confirm the validity of maps
- Analysis of RMSE, quality factors and receiver biases for 6 month period

Correspondence to:
T. M. Matamba,
mtshimangadzo@sansa.org.za

Citation:
Matamba, T. M., & Danskin, D. W.

Abstract In this paper, the second version of SANSA's Total Electron Content (TEC) maps is presented with its associated methodology and assumptions. The method is based on Ma and Maruyama (2003, https://doi.org/10.5194/angeo-21-2083-2003) determination of receiver bias and hence TEC for individual receivers. By combining values of slant TEC from 20 South African Trignet stations, maps of TEC, spatial gradient of TEC and temporal gradient of TEC can be determined. Quality factors and error of fit are determined for each map and are analyzed to identify the level of validity for TEC maps. In addition, the first operational estimation of TEC gradients both temporal and spatial are presented and discussed for the 4–5 November 2021 negative ionospheric storm. The TEC from the maps shows good agreement with the ionosonde TEC and AfriTEC model.

"The TEC from the maps shows good agreement with the ionosonde TEC and AfriTEC model".

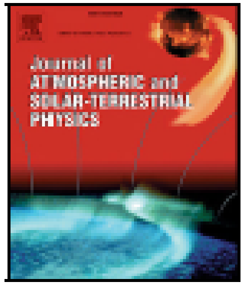
3-D Global Electron Density Model (3DNN) - Reference paper

Journal of Atmospheric and Solar–Terrestrial Physics 221 (2021) 105702

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar–Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp



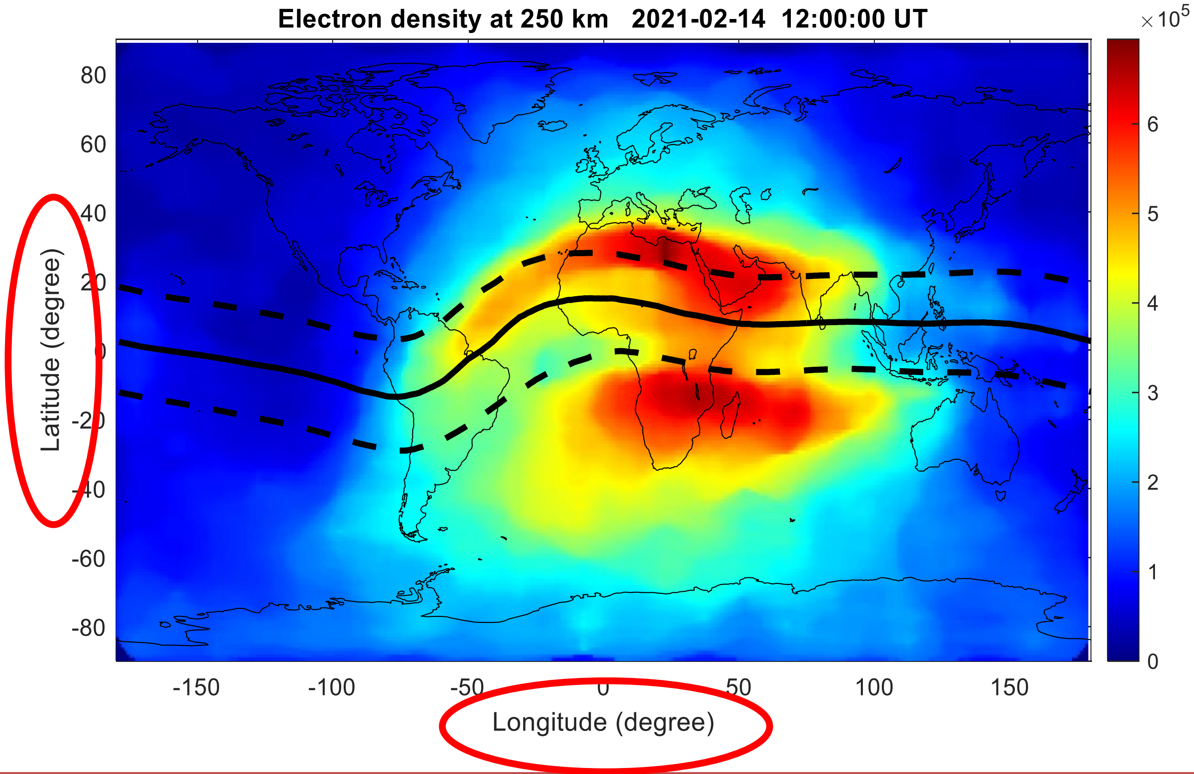
ELSEVIER

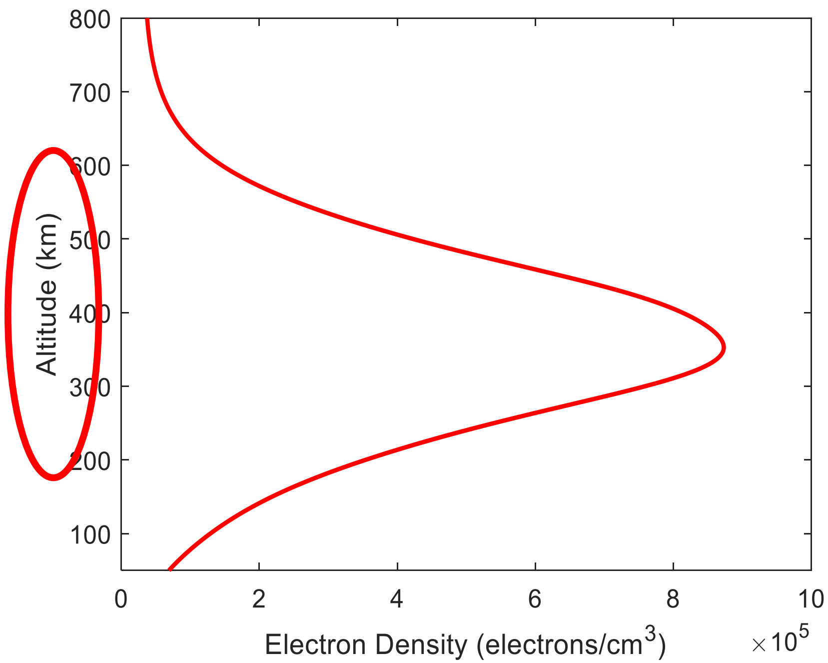
Research paper

A global 3-D electron density reconstruction model based on radio occultation data and neural networks

John Bosco Habarulema [a,b,*], Daniel Okoh [c,d], Dalia Burešová [e], Babatunde Rabiu [c,d], Mpho Tshisaphungo [a], Michael Kosch [a], Ingemar Häggström [f], Philip J. Erickson [g], Marco A. Milla [h]

3DNN - Intro





In our context, the 3-D ionospheric model involves representation of the ionosphere (electron densities) in 3 space dimensions of Longitude, Latitude, and Altitude.

3DNN - Data and Methods

- Global radio Occultation electron density profiles from COSMIC mission [Second level (ionPrf) data]
- Ionosode electron density measurements
- ISR electron density measurements
- SWARM LP in-situ electron density measurements

3DNN - Data and Methods

Data cleaning

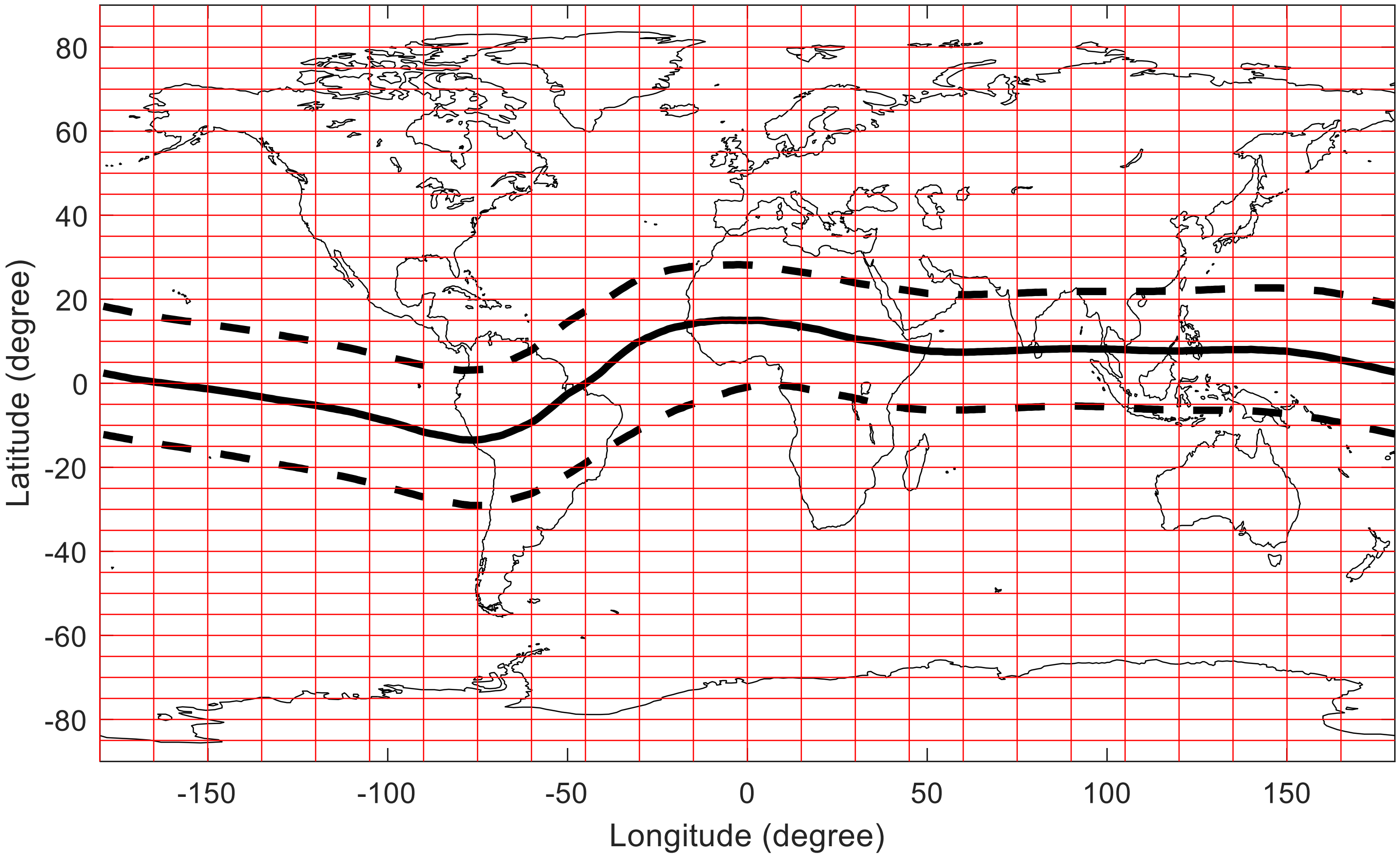
For the purpose of quality control of the data, we did the following:

(i) removed negative electron density measurements

(ii) removed the entire profiles if they have negative electron densities at altitudes greater than or equal to 100 km,

(iii) eliminated entire profiles in which the heights of peak electron densities (hmF2) are outside the range 200-550 km

3DNN - Data and Methods



The global dataset is too large (about 2 billion data points)

We therefore split the globe into 864 cells.

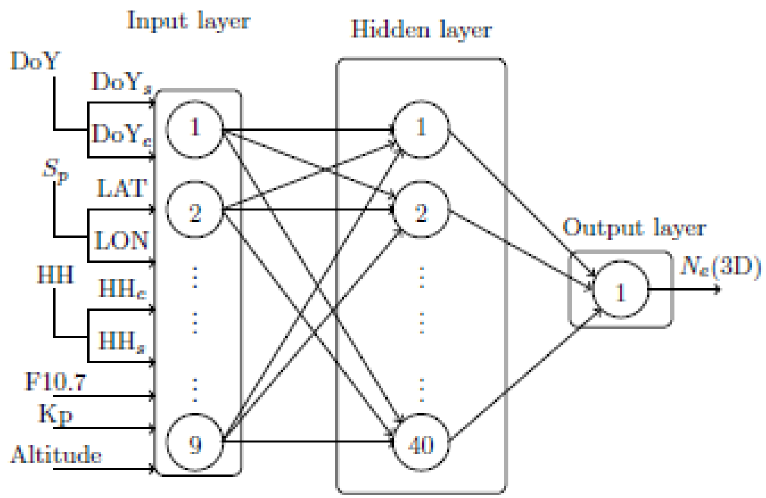
The size of each cell is 5° × 15° degrees (Latitude and Longitude)

3DNN - Data and Methods

Inputs for the neural network training:

$$DOY_s = \sin\left(\frac{2\pi \times DOY}{365.25}\right) \qquad DOY_c = \cos\left(\frac{2\pi \times DOY}{365.25}\right),$$

$$HH_s = \sin\left(\frac{2\pi \times HH}{24}\right) \qquad HH_c = \cos\left(\frac{2\pi \times HH}{24}\right),$$



Hour of the Day in UT (HH)	HHc
	HHs
Day of the Year (DOY)	DOYc
	DOYs
Spatial components	LATITUDE
	LONGITUDE
	ALTITUDE
Solar and magnetic activity indicators	F10.7
	Kp

3DNN – Results and Discussion

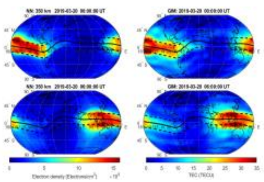
Model Validation with GIM

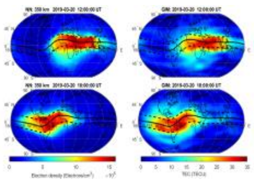
3D-NN

GIM

3D-NN

GIM



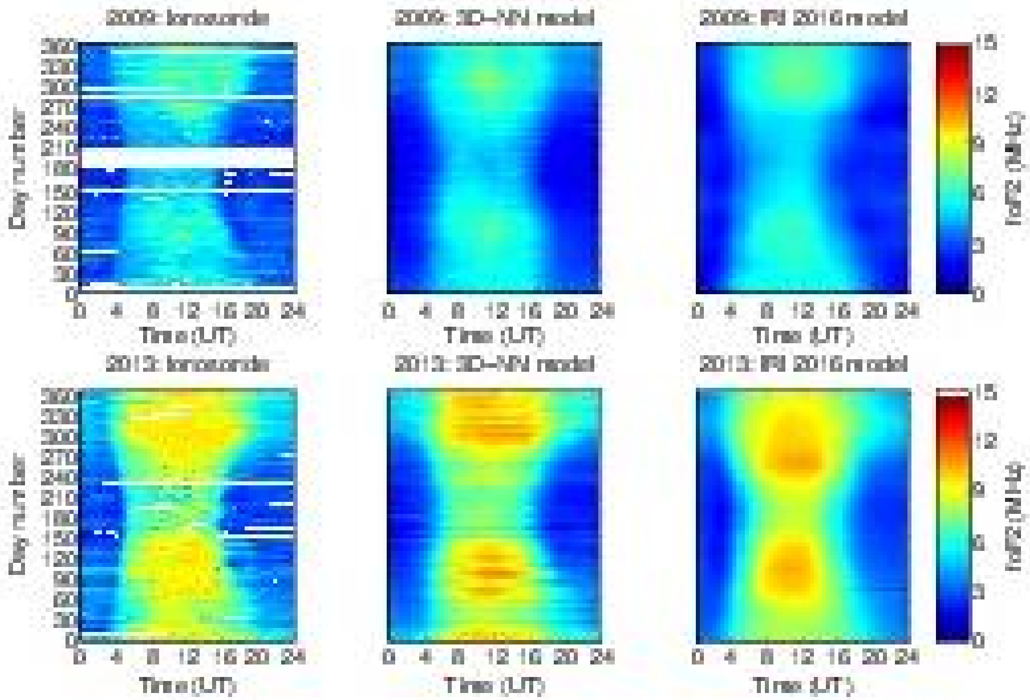


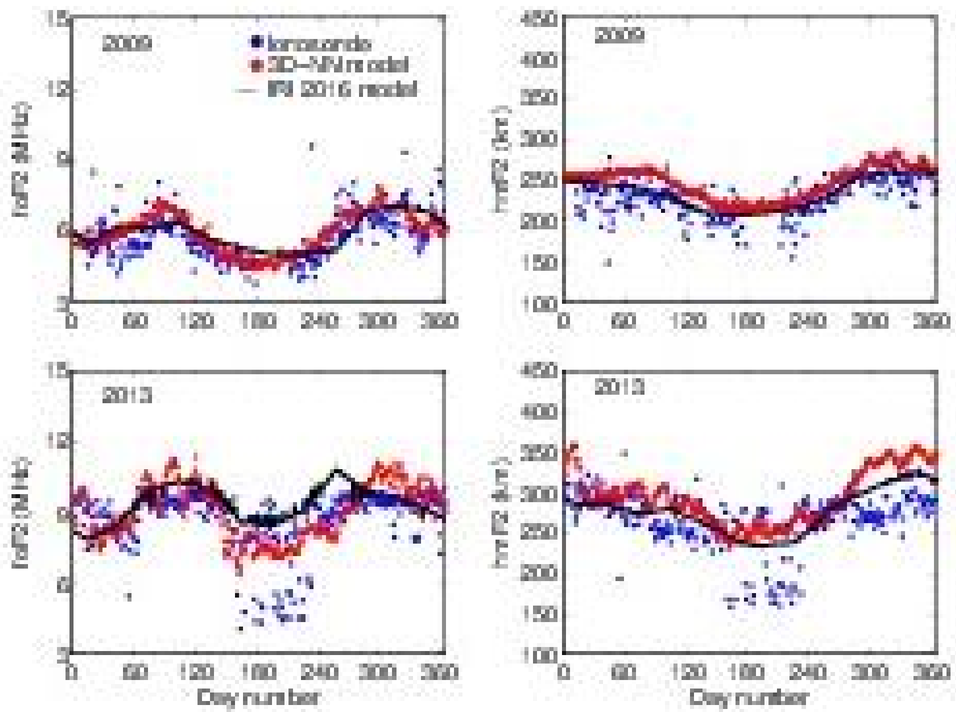
3DNN – Results and Discussion

Model Validation with Ionosonde data and IRI model

Ionosonde | **3D-NN** | **IRI**

Grahamstown (33.3 °S, 26.5° E), South Africa





3DNN – Results and Discussion

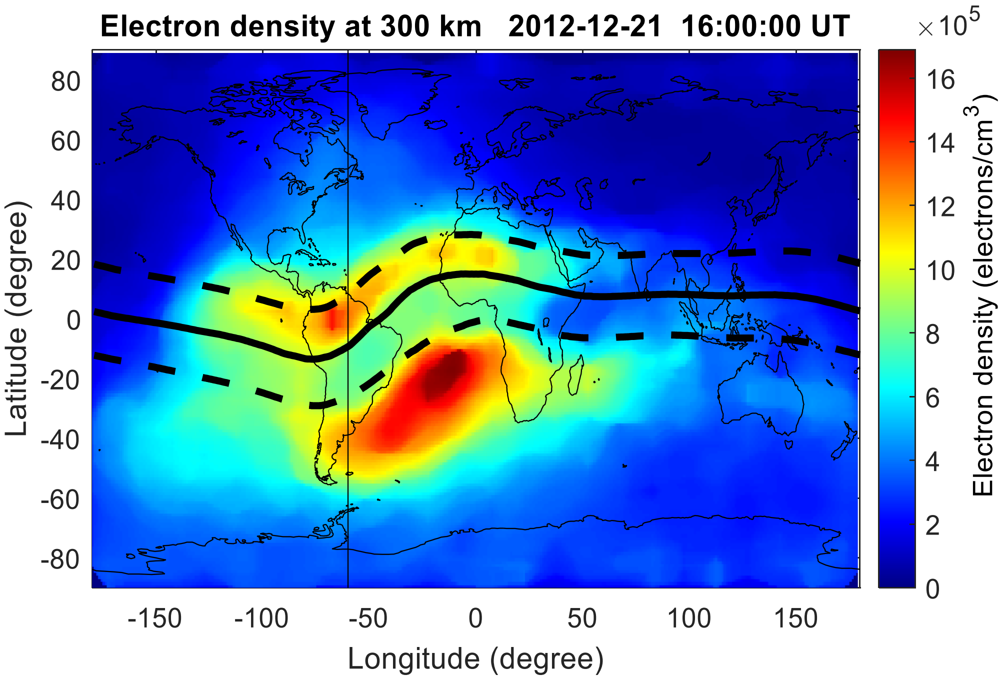
Investigating the distance between anomaly crests

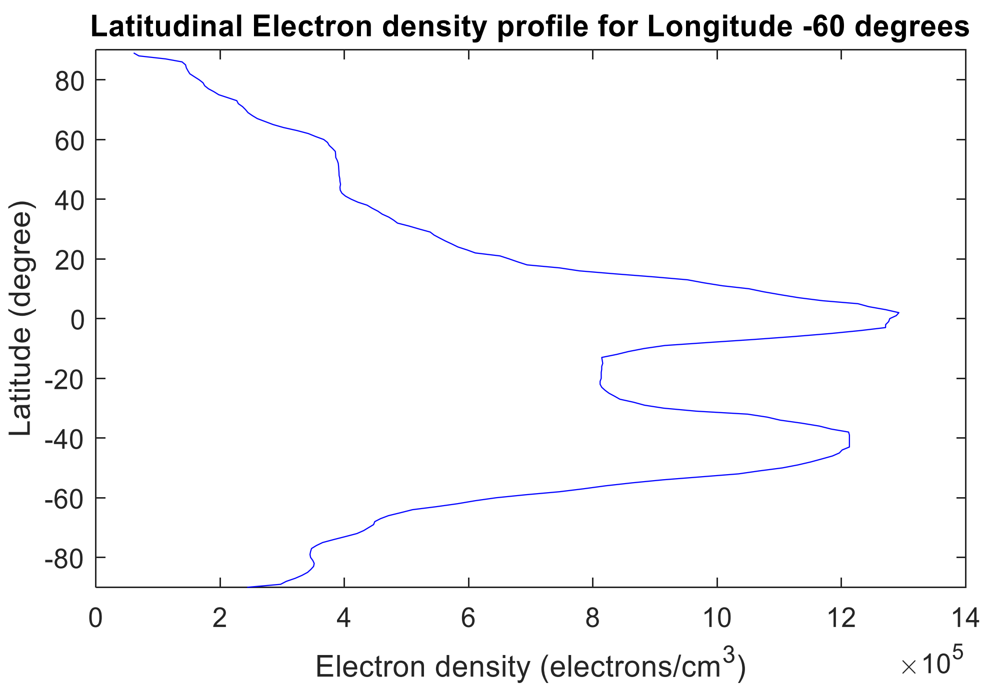
At various altitudes, and
Longitudinal sectors of the globe

3DNN – Results and Discussion

Equatorial ionization Anomaly descriptions (Position of crests)

Sample American Sector (Longitude -60°) **December solstice (21 Dec. 2012)**
Local midday (16:00 UT) **300 km**

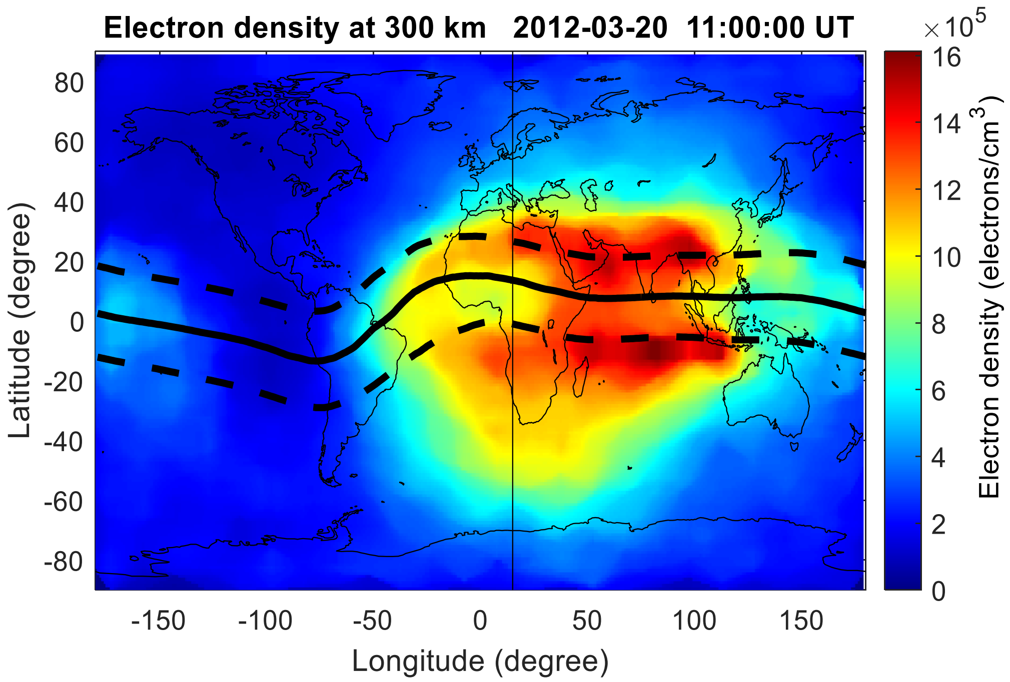


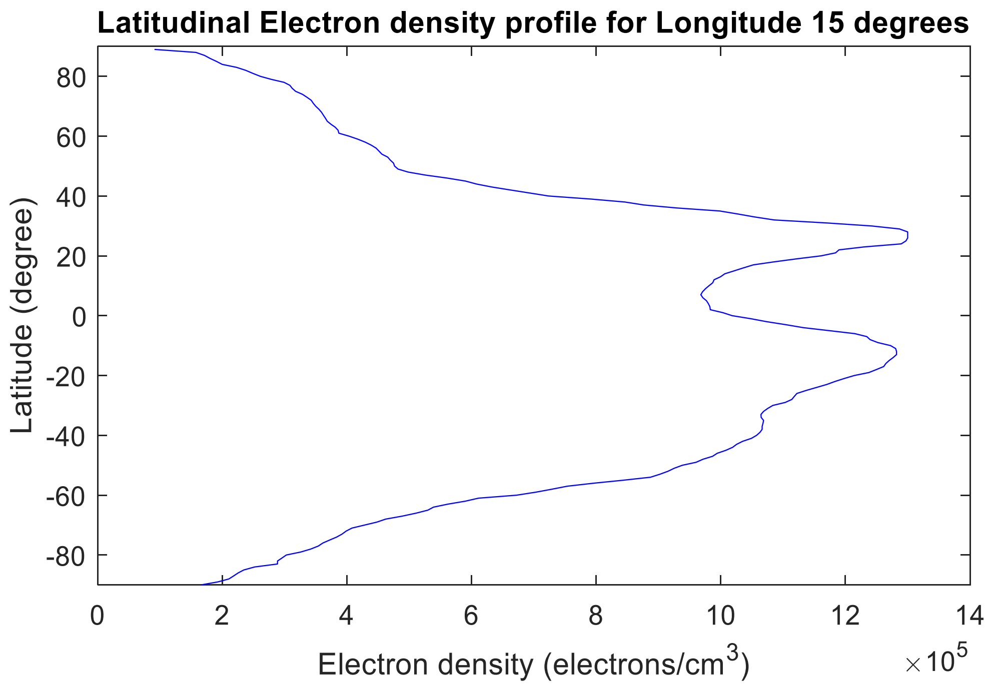


3DNN – Results and Discussion

Equatorial ionization Anomaly descriptions (Position of crests)

Sample African Sector (Longitude 15°) **March equinox (20 March 2012)**
Local midday (11:00 UT) **300 km**

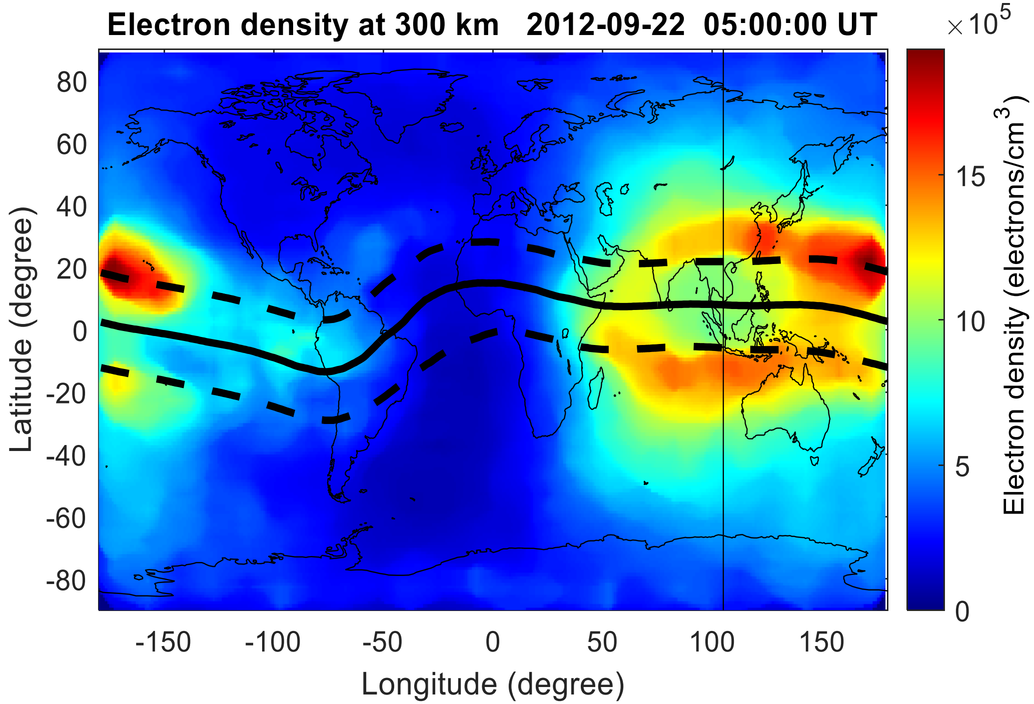


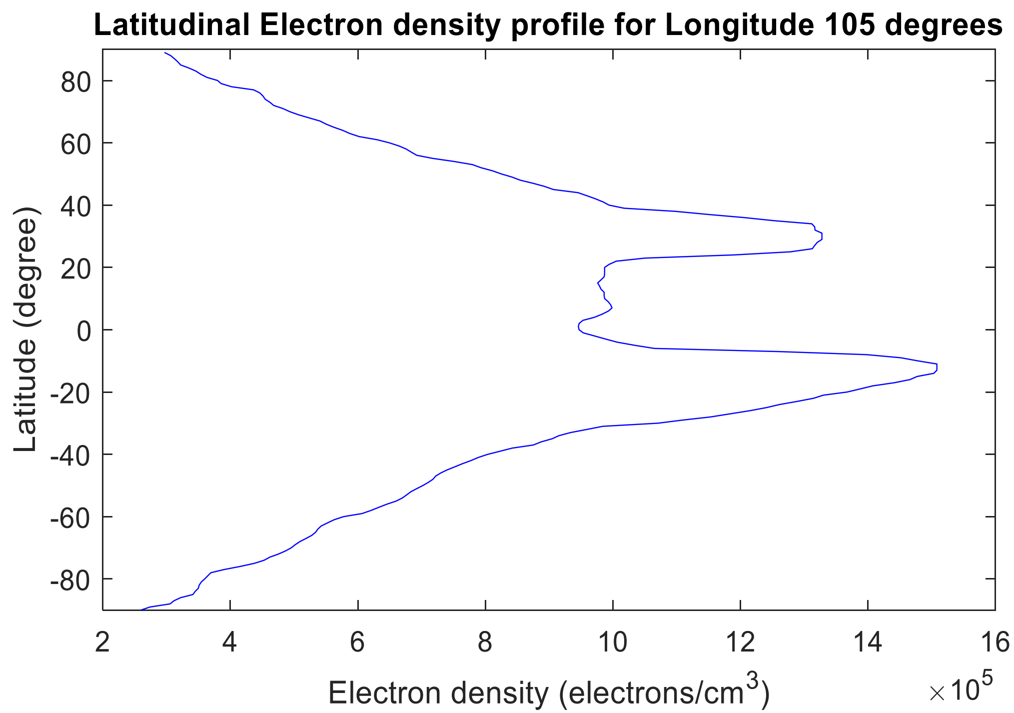


3DNN – Results and Discussion

Equatorial ionization Anomaly descriptions (Position of crests)

Sample Asian Sector (Longitude 105°) **September equinox (22 September 2012)**
Local midday (05:00 UT) **300 km**





Thank you