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Study of functional Ionospheric Models

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The ionosphere has played an important role for propagation of electromagnetic waves. They contribute to a major portion of the propagation delay, especially for the low frequency navigation signals, as they pass through earth's atmosphere. The amount of delay of these signals depends on ionospheric total electron content, which has a spatio-temporal variation. While the dual frequency users can remove the delay errors in signals, these delays pose a major threat mostly for single frequency users, who has to resort to the ionospheric models for the removal these delay errors in the signals, and hence for improving the positioning accuracy. This work has reviewed various Ionospheric Models, both theoretical and Empirical, which have been designed for a better determination of variation of TEC values. These models, still useful for both the navigation and other scientific purposes are important for understanding the characteristics of the ionosphere and gaining insight about its temporal and spatial variations.

Keywords: Ionospheric Models, Empirical models, Physics Model, Near-real Time Model

1 Introduction

The ionosphere has been studied for more than 50 years, and the basic processes underlying its behaviour have been well established. It is now well known that the main source of ionization and energy for the ionosphere is solar EUV and x-ray radiation. The solar photons ionize the neutrals in the upper atmosphere, which leads to both thermal ions and photoelectrons. In addition, the magnetospheric electric fields, neutral winds, space weather, gravity and various other factors play significant roles in the formation, loss and transport of these particles[1]. The various chemical, transport, and radiative processes operate on and in the ionosphere. However, their effects are different at high, middle, and low latitudes. As a consequence, the ionosphere displays different characteristic features in the different latitudinal regions.

Because of the importance of the ionosphere, there have been numerous approaches to ionospheric modelling over the years. Different researchers have used different approaches for modelling this dynamic behaviour of the electron density distribution of the ionosphere.

Broadly, these approaches can be categorized into physics-based models, analytical/ semi-empirical/parameterized models, empiricalmodels, and real time data driven models.

In addition, some hybrid approaches have also been used by certain researchers.

All of these model types have been used in various applications. In this paper, we provide a short glimpse of the different types of models developed for the ionosphere under these categories.

2 Materials and Methods

2.1 Physics based Models

Physical or first-principle models are useful for describing the dynamic behaviour of the ionosphere. These models solve for the electron distribution as a function of the appropriate spatial coordinates and time, with given conditions maintaining the conservation equations for the ions and electrons. If the physics and chemistry in the physical models are correct, the calculated plasma parameters should describe the real ionosphere. So, when the necessary inputs are appropriately provided to these models, these models will work in a self-consistent manner and can predict the exact behaviour of the ionosphere with time, irrespective of the fact that such event has been exhibited or not in past. This feature is not available with any other models, which are mainly dependent upon the prior behaviour of ionosphere. They can be powerful tools to understand the physical and chemical processes of the upper atmosphere.

On the flipside, the physical ionospheric models require all the participating magnetospheric and

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atmospheric inputs, which are different for different regions and time. The accuracy of a model's output depends on the quality of the inputs. Providing so many factors sometimes become difficult, if not impossible. So, erroneous inputs may lead to unreliable quantitative results. Hence, the construction of a coupled model is challenging.

2.1.1 Chapmans Model

This model, developed by mathematician Sydney Chapman[2,3], gives a theoretical descriptive overview of the ionospheric production rate and electron density in terms of solar flux and related geometry. The basic assumptions of this model primarily include the horizontal stratification of the earth's atmosphere and ionization of single-constituent atmospheric particles by monochromatic solar radiation. It is a primitive model of the ionosphere, which, however can correctly describe the dependence of the ionization with solar parameters. The neutral particle density is given as a function of height as

$$N(\mathrm{h}) = N_0 e^{-\frac{h}{H}} \quad \dots (1)$$

where, H represents the scale height and h is the height at which we consider a vertical layer of atmosphere having thickness dh.

The production function for ionization per unit volume or the production rate is given by

$$q(\mathrm{h},\chi) = k\sigma n_0 S_0 e^{\{-\frac{h}{H} - \sigma n_0 H e^{\left(-\frac{h}{H}\right)} sec\chi\}} \quad \dots (2a)$$

where, χ is the solar zenith angle and k, σ, n_0 and S_0 are constants.

The production function can also be expressed as

$$q(\mathrm{h},\chi) = q_0 e^{\{1-z-e^{-z} sec\chi\}} \quad \dots (2b)$$

where, z = $(h - h_{m0})$/H is the reduced height with h_{m0} taken as the height of maximum production function.

For lower heights, where neutral particles is maximum, the electron density is given by

$$N_e(z) = \sqrt{\frac{q(z)}{\alpha}} \quad \dots (3)$$

For higher altitude, where concentration of neutral particle decreases, the electron density is given by

$$N_e(z) = \frac{q(z)}{\beta} \quad \dots (4)$$

Here, α and β are the recombination coefficients at different heights and q is the production rate, etc. Figure 1 shows the vertical variation in the production rate derived from the Chapman's Model.

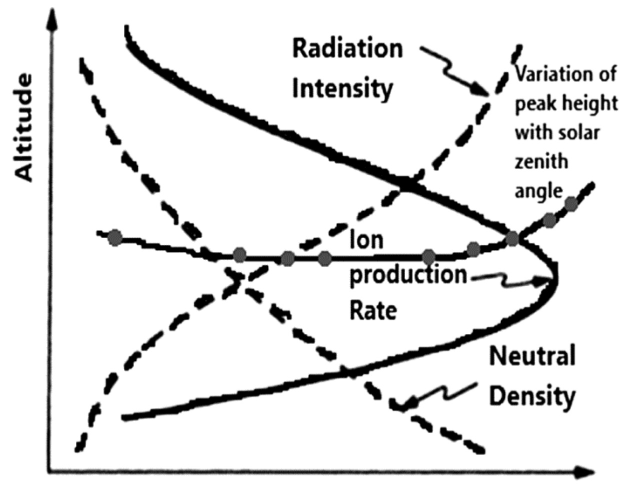

Fig. 1 — Production rate as a function of height derived from Chapmans function.

The graph displays the fact that the production function has a maximum value at χ=0 i.e., when the sun is overhead. So, as the zenith angle χ increases, the height of maximum production function also shifts towards the higher altitudes, thereby decreasing the maximum production function value.

However, the theory needs a modification for the case for grazing elevation angle value, i.e., the zenith angle of the sun is too high, since, in that case, it is necessary to consider the curvature of the Earth which violates the initial assumption of this theory i.e., the Earth's atmosphere is horizontally stratified.

2.1.2 Utah State University Global Assimilation of Ionospheric Measurements (USU-GAIM) or (USU Model)

One of the earliest models in this direction was the USU model of the global ionosphere[4] developed in conjunction with NRL's MHD model of the magnetosphere[5]. The MHD magnetosphere model calculates convection electric fields and field-aligned currents, from which the electron distribution can be obtained in terms of time and location[6].

This effort of USU is called Global Assimilation of Ionospheric Measurements (GAIM) and hence is often named as (USU GAIM). This is a Gauss-Markov Kalman Filter (GMKF) model and involves both physics -based model of ionosphere as well as Kalman Filter as a basis for assimilating a diverse set of real time (or near real-time) measurements. The physics-based model is the Ionospheric Forecast Model. It is global and includes the D, E and F region of the ionosphere and topside from 90 km to around 1400km, involving five ion species namely NO+,O2+,N2+,O+ and H+.

2.1.3 Coupled Thermosphere Ionosphere Plasmasphere Model (CTIP)

This model, developed in the Sheffield University, is a three dimensional, fully coupled, numerical model of the thermosphere, low latitude plasmasphere and high latitude ionosphere system. In this model the solution of the plasma density is obtained based on solving the equations of continuity, momentum and energy balance[7]. The current versions of CTIP have resulted from over twenty years of development.

At present, CTIP model is coupled with Weimer ionosphere electrodynamics model which calculates ionospheric electric fields for solar wind parameters namely density, solar wind velocity magnitude, IMF magnitude and clock angle) and earth's dipole orientation as input on 12-minute temporal grid.

He+ layering in the topside ionosphere was observed in post-midnight hours at both solar maximum and minimum conditions under observations made by Arecibo incoherent scatter radar. A study was conducted using CTIP model which accurately displayed both the He+ layer as well as regions of He+ dominance[8].

2.1.4 Time Dependent Ionospheric Model (TDIM)

This model solves a set of equations involving different ions and electrons. Both dynamic and photo chemical processes are considered[9,10]. The model depends on EUV91 model data for solar radiation flux, MSIS 86 for neutral concentration and temperature and HWM 90 for neutral horizontal winds. Inputs are geographical latitude and longitude, day number, Ap index and daily and 81-day mean of F10.7. Output are electron and ion concentrations at a function of time and altitude.

The neutral wind of ionosphere affects both height of F layer as well as the total electron content, but most of the presently available models of thermospheric wind do not appear to represent it perfectly. A study was carried out where ionosonde observations of F region peak in mid-latitude ionospheric region of several decades were used to compare the effectivity of several neutral wind models, when these models are used as drivers for ionospheric models. Results indicated that Utah State University Time Dependant Ionospheric Model (USU TDIM) showed a more convincing output[11].

2.1.5 Sheffield University Plasmasphere Ionospheric Model (SUPIM)

SUPIM is physics-based model of the Earth's ionosphere that describes the distribution of ionization within the Earth's mid-latitude to equatorial-latitude ionosphere and plasmasphere. The model includes both physical and chemical processes, the principal processes being ion formation due to solar EUV radiation, thermospheric meridional and zonal winds, E x B drifts, photoelectron heating along with local heating and cooling mechanisms. It involves solution of time-dependant equations of continuity, momentum and energy balance for the O+, H+, He+, N2+, O2+ and NO+ ions and the electrons, along with closed magnetic field lines for the ion and electron concentrations, field-aligned velocities and temperatures. The magnetic field is assumed to be an eccentric-dipole representation of Earth's magnetic field.

Recent studies with this model has proved the existence of an additional F3 layer, at latitudes close to the magnetic equator, where the peak electron density of F3 layer can even exceed that of F2 layer at noon when at E x B drift if large[12]. Also, the equatorial ionization anomaly (EIA) development using TEC values were studied with the help ofGPS signals, appeared to agree with those modelled using SUPIM as well as International Reference Ionosphere (IRI-2012) simulation results[13]. With the SUPIM model, it is possible to determine vertical E x B drift velocities at the equator as well as magnetic meridional winds. Studies have been carried out to determine the same[14].

Table 1 provides the synopsis of the mentioned theoretical models. Theoretical ionospheric models proved to be perfect in providing a deeper insight to the actual physical and chemical processes taking place in the ionosphere. Most of these models, in general, solve equations of continuity, momentum and energy balance on the basis of various input parameters, thus providing electron and ion concentration as a function of height. Still, they possess their own versatility in working in different ionospheric as well as thermospheric and plasmaspheric latitudes.

2.2 Analytical/ Semi -empirical models

The physical (numerical) models discussed in the previous section provide a great deal of information on the ionospheric parameters. Typically, the ion and electron densities, and other parameters are obtained as a function of altitude, latitude, longitude, and universal time. However, the physical models are usually difficult to run and require an excessive amount of CPU time. Therefore, it is not at all convenient for the utilization by general users. Yet, the useful outputs of these models cannot be dispensed with. In order to obtain the benefit of physical model results and yet making it simple, the analytical models were developed.

Analytical or Semi-empirical models are based on the analytical description of the ionosphere with functions derived from experimental data or are adapted from physical models. These models, fit the extensive output of the physical models with relatively simple analytical functions of bare necessary inputs. This makes the theoretical output quickly and easily accessed using limited inputs in simpler functions. Models of this type have been developed for the low, middle, and high latitude regions of the ionosphere.

2.2.1 Semi-Empirical Low-Latitude Ionospheric Model (SLIM)

Anderson et al.[15] developed the Semi-Empirical Low-Latitude Ionospheric Model (SLIM) for the low latitude region. This model provides electron and ion density profiles for every half-hour of local time for a 24-hour period. Nine separate sets of SLIM parameters were generated that covered three levels of solar activity (low, medium, high) and three seasons (summer, winter, equinox). The coefficients were fit with harmonic terms to describe the local time variations. The output from the SLIM model is the peak electron density and other ionospheric parameters.

2.2.2 Parameterized Ionospheric Model (PIM)

It is a fast global ionospheric and plasmaspheric model based on a combination of the parameterized output of several regional theoretical ionosphere models and an empirical plasmaspheric model [16].From a given set of geophysical conditions (day of the year, solar activity index f10.7, geomagnetic activity index Kp) and positions (latitude, longitude, and altitude), PIM produces electron density profiles between 90 and 25000 km altitude, corresponding critical frequencies and heights for the ionospheric E and F2 regions, and Total Electron Content (TEC)[17,18,19,20,21,22].

Table 2 provides a synopsis of the analytical/semi-empirical models. Analytical models are developed out of the physical models where these analytical models uses the results of the Physics-based models, thus making them simpler. Though these models are

Table 1 — Synopsis of the theoretical models

Model Name	Characteristics	Input Parameters	Output Parameters
Chapmen's model	Simple but primitive, explains the dependence of ionization with solar parameters.	Height (h) and elevation angle (E)	Production function, electron density
USU model	Involves both Kalman Filter Model and physics-based model, assimilates real-timemeasurements. takes into account of five ion species namely NO+, O2+, N2+, O+, H+.	Time and location	3-D electron density distribution and vertical TEC at specified times. N_mE,h_mE, N_mF_2,$h_mF_2$also provided.
CTIP model	Coupled numerical model of thermosphere, low latitude plasmasphere and high latitude ionosphere system. coupled with Weimer ionospheric electrodynamics model	Time and location	Ionospheric electric fields. 3-D electron density
TDIM model	Dynamic and photo chemical processes are considered	Geographical latitude and longitude, day number, Ap index and daily and 81 day mean.	Electron and ion concentration as a function of time and altitude.
SUPIM model	Describes ionization distribution within Earth's mid-latitude to equatorial-latitude ionosphere and plasmasphere.	Time and latitude	Electron and ion concentrations as a function of time.

Table 2 — Synopsis of the analytical / semi-empirical models

Model Name	Characteristics	Input Parameters	Output Parameters
SLIM model	Low latitude ionospheric model. Provides electron and ion density profiles for every half an hour of local time in a total of 24 hours.	Time and latitude	Peak electron density and other ionospheric parameters.
PIM model	Fast global ionospheric and plasmaspheric model.	Set of geophysical conditions and position.	Electron density profiles between 90 to 25000km altitude, corresponding frequencies and heights for ionospheric E and F_2 regions and TEC.

dependent on Theorical model output, still these models provide a study ofthe low, middle and high latitudinal ionospheric regions.

2.3 Empirical models

Empirical models are data-driven models which gives a description of the ionosphere and ionospheric parameters with the help of mathematical functions derived from the experimental data. These models are easy to use for assessment and prediction purposes. Data sources for this model includes ground ionosondes, topside sounders, incoherent scatter radars, rockets and satellites.

Since Empirical models are data-driven, they thus avoid the uncertainties and the rigorous calculations involved in theoretical ones. They depend on the pragmatic data, partially or totally, to provide information about the variational form of electron density of the ionosphere.

Depending on their extent of validity, these models can be either local or regional or global in nature. Local ionospheric models are designed to provide information about localized phenomena and hence are restricted to a particular zone[1].

2.3.1International Reference Ionosphere (IRI)

International Reference Ionosphere model was developed as a part of an international project sponsored by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI). It aimed at producing a reference model of the ionosphere based on available experimental data sources. IRI is updated periodically and has evolved over a number of years[23]. IRI data sources are derived from many pre-existing models and experimental values. As output, it gives the electron density profile and other parameters in terms of time and space[24,25,26].

IRI model and software are updated yearly during special IRI Workshops according to the decisions of IRI Working Group. The main input parameters include electron density, electron temperature, ion temperature, ion composition (O+, H+, He+, N+, NO+, O2+, Cluster ions), equatorial vertical ion drift, vertical ionospheric electron content, F1 probability, spread-F probability, auroral boundaries and effects of ionospheric storms on F and E peak densities.

IRI model has an online web version that enables computation and plotting of IRI parameters mentioned above[27].

2.3.2 Klobuchar model

The Klobuchar Ionospheric Model was designed to minimise the user computational complexity and to keep a minimum number of coefficients, which can be transmitted on satellite link. The model is primarily designed to serve the navigational requirements of ionospheric corrections. This model assumes a thin shell of electron content at a height of about 350 km using which the vertical and slant ionospheric delay can be calculated using a half cosine function and six transmitted coefficients. The model is capable of removing more than 50% of the ionospheric delay across the globe.

The Klobuchar algorithm to run in a single frequency receiver is provided in steps as follows[28]:

Given the user approximate geodetic latitude ϕ_u, longitude λ_u, elevation angle E and azimuth A of the observed satellite and the coefficients αn and βn broadcasted in the GPS satellite navigation message, the vertical ionospheric delay is given as:

$$I_{L1\,GPS} = \left[5.10^{-9} + A_I \cos\{\frac{2\pi\,(t-50\,400)}{P_I}\}\right] \; ; \; |X_I| \le \pi/2$$

$$= 5\,.\,10^{-9} \; ; \; |X_I| \ge \pi/2$$

Here, $A_I = \sum_{n=0}^{3} \alpha_n \phi_m^n$ in seconds and $X_I = \frac{2\pi\,(t-50\,400)}{P_I}$. ϕ_m is the geomagnetic latitude of the location and t is the local time. Figure 2 shows the variation of the TEC over a complete day derived from the Klobuchar model.

The vertical delay can be converted to slant delay along any signal path of elevation E, using the conversion relation

$$F = 1.0 + 16.0(0.53 - E)^3$$

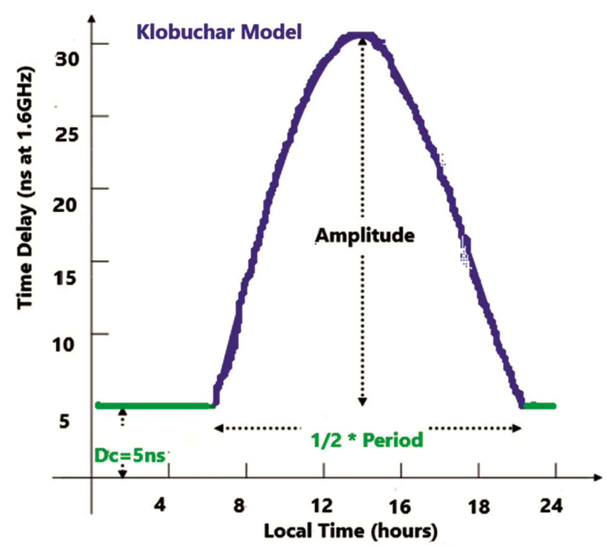

Fig. 2 — Diurnal variation of TEC derived from Klobuchar model.

The above algorithm provides the delay for L1 frequency band of GPS, i.e., 1575.42 MHz. However, this can be converted to Total Electron Content using the linear conversion relation

TEC = Delay in L1 / 0.16

The figure represents the Klobuchar estimation of ionospheric delay for a particular location. It displays the vertical TEC variation with time for the chosen location. It is clear from the graph that for ½*Period, the vertical TEC variation resembles a half sinusoidal-wave. However, the width and amplitude of the graph may be different for different locations.

Klobuchar model approximately reduces 50% of the ionospheric impairments with its coefficients which is not effective for single frequency GNSS users while working at critical applications. A lot of recent studies are still going on for providing more accurate and improved data[29]. Hence, to improve the accuracy level, a new model, using the Klobuchar Model driven by Auto Regressive Moving Average Method (SAKARMA) was developed to forecast and increase the precision of ionospheric effects[30,31,32].

2.3.3 Ne-Quick model

Ne-Quick is a three-dimensional and time dependent ionospheric electron density model. It is a quick-run model designed particularly for the trans-ionospheric applications that allows calculation of electron concentration at any given location in the ionosphere. This can therefore be used to estimate the Total Electron Content (TEC) along any ground-to-satellite ray-path with the help of numerical integration[33,34]. It is derived from an empirical climatological representation of the ionosphere, which predicts monthly mean electron density from analytical profiles. The model is dependent upon solar- activity -related input values: sun spot number or solar flux, month, geographical latitude and longitude, height and Universal Time (UT). This model is adapted for real-time Galileo single frequency users in order to derive real time predictions of ionospheric delays, using three coefficients broadcasted in the navigation message.

In order to take into account both daily variation of the solar activity and the user's local geomagnetic condition, the NeQuick-G model computes the daily effective ionization level (*Az*) expressed in solar flux unit ($10^{-22} Wm^{-2} Hz^{1}$). For Galileo single-frequency users, Galileo satellites broadcast three ionospheric coefficients, viz. a_0, a_1 and a_2, in their navigation message that are used to compute the A_z as follows (Galileo - Open Service SIS-ICD, 2016):

$$A_z = a_0 + a_1\mu + a_2\mu^2 \quad \dots (1)$$

where μ is the modified *dip* latitude, or *MODIP*, derived as

$$\tan\mu = \frac{I}{\sqrt{\cos\phi}} \quad \dots (2)$$

being *I* the true magnetic inclination, or *dip* in the ionosphere (usually at 300 km), and ϕ the geographic latitude of the receiver[35].

Table 3 provides a synopsis of the Empirical Models. Empirical models are generally data-driven, which describes ionosphere and ionospheric parameters based on mathematical functions derived from the experimental data. Hence, unlike the theoretical and analytical models, these models are easy to implement and does not involve complex mathematical calculations.

2.4 Near real time algorithms

In recent years, particularly due for the usage in satellite navigation and other similar applications, developing real-time data-driven algorithms for estimating the ionospheric parameters have become popular. Though these are loosely termed as 'Models' actually, they are interpolation or prediction algorithms. These models require in-situ measurements of the ionospheric variables, on the basis of which the output parameters are derived.

Table 3 — Synopsis of the empirical models

Model Name	Characteristics	Input Parameters	Output Parameters
Klobuchar model	Minimizes user computational complexity. Keeps minimum number of coefficients transmitted on a satellite link. Capable of removing 50% ionospheric delay across the globe.	Time and latitude	Diurnal variation of vertical TEC values with respect to time for a particular location.
IRI model	A reference ionospheric model based on available experimental data sources. Online web version available.	Date and time, day and month of the year, latitude, longitude and height.	Electron and ion densities along with TEC values at corresponding heights.
Ne-Quick model	Quick run 3-Dimensional time dependant ionospheric electron density model.	Day, time and latitude	Electron concentration at any given ionospheric location.

These algorithms, based upon the kind of intelligence used for deriving the output.

2.4.1 Ionospheric Grid model

The major sources of error in using conventional primary Satellite-based navigation is ionospheric propagation delays. This delay errors needs to be corrected by using suitable ionospheric model to improve the signal accuracy. For precision landing of aircrafts over Indian airspace, an Ionospheric Grid model has been developed. In this system, due to complex ionospheric structures and large TEC variations, precise determination of ionospheric propagation delays becomes critical. To provide the users with the corrections necessary for the ionospheric delay, Grid based ionospheric model is employed, in which the vertical TEC or the vertical ionospheric delay is transmitted to the user in near real time at definite grid points, defined over the earth surface. These grid points are internationally defined (RTCA, 1999) and are typically separated by 5° in both latitude and longitude.

One such model is developed for the Indian SBAS system GAGAN[36] and provided much higher accuracy for the ionospheric delay correction compared to the empirical models like Klobuchar and NeQuick along with other advantages[37] . A relative comparison of vertical TEC using spatial plots derived from Klobuchar model, NeQuick model and GAGAN is shown in the Fig. 3. More improved ionospheric models are also developed[38].

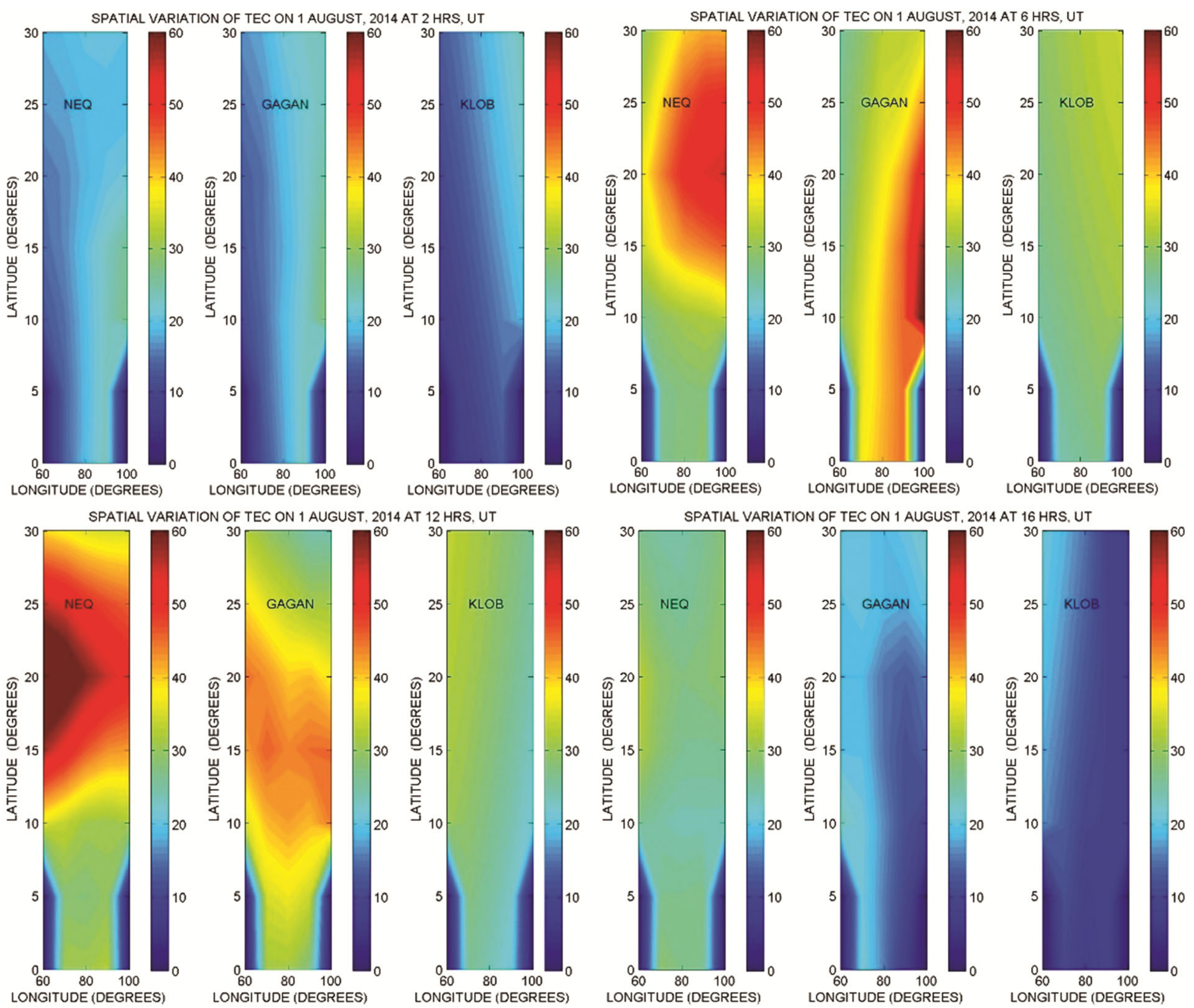

Fig. 3 — Relative comparison of vertical TEC using spatial plots derived from Klobuchar model, NeQuick model and GAGAN at 0200 hrs UT, 0600 hrs UT, 1200 hrs UT and 1600 hrs UT respectively.

2.4.2 Machine learning based predictions

KF based predictions - Kalman Filteringis quite helpful for determination of ionospheric delays of the signals and thus the Total Electron Content (TEC) variations in ionosphere.One such study involves continuous estimation based on single frequency TEC inputs, showed moderate accuracy for the mid latitude stations, but much better results were obtained for calibrated mode with no seasonal dependence. When compared with Klobuchar Model estimations, the calibrated estimation has much better performances, conspicuously for mid latitude stations[39]. Studies have been carried out that use of Kalman-Filter based algorithm that estimates both ionosphere and plasmaspheric electron content, the combined satellite and receiver biases, and estimation error covariance matrix in a single-site or network solution[40].

Researches show that there can beanomalous TEC variations before and after earthquakes. One such study has been carried out where the Kalman Filter approach is used to study the anomalous TEC variations before and after the earthquake. The method proved to be quite effective in determining TEC anomalies before and after earthquakes [41].

NN based Predictions - The Total Electron Content (TEC) regional models are generally based on Artificial Neural Network [42].Recent studies are going on to make predictions of TEC values using adaptive recurrent neural network to provide better delay corrections[43] .

Recent studies involve use of Artificial Neural Networks (ANN) to detect seismo-ionospheric anomalies for estimation of earthquake parameters. The work mainly focusses in investigating Total Electron Content (TEC) time series values using Multi-Layer Perception (MLP) Neural Network to detect seismo-ionospheric anomalies[44].

Another study involving Neural Network based predictions, has been recently carried out by Dabbakuti et al. (2019), where a new ionospheric prediction model, named as Singular-Spectrum Analysis Artificial Neural Network (SSA-ANN) was developed. This model is used as a pre-processing tool for prediction of ionospheric TEC based on Neural Network[45].

3 Results and Discussions

The models described here are capable of describing the ionosphere and its constituent parameters with their respective capacity of accuracy. While the physics- based models stands on a strong theoretical background involving complicated integration, the empirical models are much simpler ones and easy to use.

The theoretical ones, like the oldest model USU-GAIM or CTIP model, has been so designed that they give the user an insight on the various physical as well as chemical process that is going on in the ionosphere, along with other ionospheric parameters. Though USU is the oldest theoretical model, still it has its own versatility of working with both theoretical and Kalman Filter based approaches, thus providing real time (or near real time) measurements.

In order to make the output of these theoretical models more effective and accessible, the analytical models were developed, which works with the results of these theoretical models and are capable of providing the user with a complete idea about distribution of ionization and electron density as a function of time and altitude.

On the other hand, we have the empirical models, which are completely data-driven and works on the basis of mathematical functions taking the data as input. They are, by far, the simplest and most easy to use model. But one may rise a question on the reliability on these models, since their output may be erroneous if the input data contains errors.

All these models can be either regional or global, depending on which the extensivity of their works are designed.

3.1 Recent trends in ionospheric TEC research

Ionosphere has continued to remain as the centre of interest of many research scientists for more than 50 years and with the ever emerging and improved technologies and instruments, and design of various simulation models to study the ionospheric variability, ionospheric research has progressed a lot in the last few decades.

Ionospheric research mainly centres in estimating TEC values at different ionospheric levels for removing long-range delay errors in signals. In recent times, the TEC determination methods have shown to take a sharp bent towards the involvement of various intelligence including machine learning techniques and Artificial Neural Network methods. The algorithm depends on the type of intelligence used and these processes has proved to estimate TEC values with higher efficiency.

4 Conclusion

This work provides a detailed as well as a comparative study among different functional Ionospheric Models, which can provide a clear insight about these models to the researchers and scientists working in this field. However, every model, be it theoretical or empirical, has its own unique characteristic features along with its advantages and disadvantages. While some of the models can replicate the true variations in the ionosphere with precision, some of them really proved to be working much effectively in removing impairments in satellite signal propagation.

Recent studies have been going on fusing these models to develop an entirely new ionospheric model with a much higher accuracy which might prove to be more effective than any of these models. In recent times, with the emerging technology and use of various intelligence methods in satellite navigation systems, it has been possible to develop data-driven algorithms to derive various ionospheric parameters including TEC values. They cannot be categorized as 'models', since these algorithms generally depend on the type of intelligence used, but have proved to provide much better and faster TEC estimation. Recent ionospheric research has shown a serious advancementwith involvement of these still-evolving machine-based predictions.

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