GPS-BASED IONOSPHERE MODELING: A BRIEF REVIEW

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ABSTRACT

Ionosphere modeling has been a highly interesting subject within the scientific community due to its effects on the propagation of electromagnetic waves. Propagation of electromagnetic waves is affected by the electron density in the ionosphere. This electron density is not permanent and it can represent regular and irregular variation according to various factors. Particularly in satellite-based studies (e.g., Positioning with GPS) the structure of the ionosphere must be analyzed well and modeled for removing its effect. Various methods have been proposed for modeling the ionosphere since 1970. In recent years, GPS is used in ionosphere modeling studies extensively. In this paper, the structure of the ionosphere, some developed models and particularly GPS based ionosphere modeling studies are briefly reviewed.

KEYWORDS: Ionosphere modeling, GPS, IRI, Interpolation Techniques, PIM, Solar activity

1. INTRODUCTION

The Earth’s atmosphere has significant variations in pressure and temperature according to the altitude which define a number of atmospheric layers. Starting from the lowest the five layers are; troposphere, stratosphere, mesosphere, thermosphere and exosphere. Another layer is ionosphere which includes thermosphere and parts of the mesosphere and exosphere. It is distinguished because it is ionized by solar radiation.

The ionosphere is a part of the upper atmosphere starting at height of between 50 km to 1000 km, where the free electron density affects the propagation of radio frequency electromagnetic waves. The main constituents of the ionosphere are uncharged and charged particles. The charged particles are created by photoionization caused by incoming UV and X radiation from the sun [1]. The rate of this ionization depends on the density of gas molecules and the intensity of the radiation. In the ionosphere the particle density is extremely small and collisions between electrons and ions are relatively infrequent, so recombination takes place only very slowly. Because all the particles in the ionosphere are not charged ions and electrons; the degree of ionization is very low. In the ionosphere only the charged particles are able to influence the propagation of radio waves. Mostly the free electrons affect the propagation, since the free electrons are much lighter than the free ions. Ionospheric free electron density is highly variable because of the regular and irregular variations [2].

The ionospheric effect and its precise modeling are important for space-based observation systems as well as communication systems and space weather studies [3]. As an example the radio channel selection must consider the ionospheric condition [4]; single frequency altimetry measurements require ionospheric corrections to extract information from the measurements [5-7]; disruptions of ionosphere caused by massive solar flares can interfere with or even destroy communication systems, earth satellite and power grids on the earth [8]; and effective mitigation techniques are necessary for the adverse effects of the ionosphere on synthetic aperture radar(SAR) imaging [9]. Besides them, Global Navigation Satellite Systems are also severely affected by the ionosphere.

The widespread effect of the ionosphere on various areas has made ionosphere modeling a popular subject for about 40 years and thanks to variety of methods which are mentioned in the next sections ionosphere is modeled. However, high variation of the electron density in the ionosphere results in difficulties for its modeling. In recent years, the development of GPS and creation of extensive networks of GPS stations that provide worldwide data availability through the internet have opened up a new era in remote sensing of the ionosphere[10].

The purpose of this paper is to provide a brief review of the ionosphere modeling. In this paper section 2 describes the structure of the ionosphere. Section 3 deals with the various ionosphere modeling techniques. Section 4 provides information about modeling the ionosphere by means of GPS. Section 5 contains concluding remarks.

2. STRUCTURE OF THE IONOSPHERE

2.1 Ionospheric regions

There are three major regions of the global ionosphere. These are equatorial, high latitude and mid-latitude regions.
The equatorial region can be characterized with the highest values of the peak-electron density. The reason is the strong solar radiation and intense ionization. In the high latitude region the peak electron densities are considerably smaller than the equatorial region. However short time variation of the electron density is much more than equatorial region [11, 12]. The mid-latitude region is the least variable and undisturbed when compared with the other regions. It is the best observed due to the fact that most of the ionosphere-sensing instruments are located in this region.

### 2.2 Ionospheric layers

The ionosphere layers start from 50 km and extend to 1000 km (Fig. 1). In fact the upper boundary of the ionosphere is not well defined since it can be interpreted as the electron densities thinning into the plasmasphere [13]. Because of the different atoms and molecules in the atmosphere and their variant rates of absorption, a series of distinct layers of electron density exist. These are denoted by D, E, F1 and F2 layers. Detailed explanations of the ionospheric layers can be found in e.g. [14, 15].

![Figure 1 - Vertical profile of the ionosphere](image)

#### 2.3 Ionospheric disturbances

The electron density in the ionosphere changes because of various factors. This variation appears as regular or irregular variations [2].

- Diurnal period of the earth, season, solar cycle, are given as examples causing regular variations, whereas ionospheric and geomagnetic storms, traveling ionospheric disturbances (TIDs) and ionospheric scintillations, are given examples of factors causing variations of irregular character.

#### 2.4 Solar terrestrial indices

Irregular variations of the ionosphere are associated with geomagnetic effects. Skone and Cannon [11], Nishino et al. [17] and Ping et al. [18] have modified by their studies that with the increase in the geomagnetic effect, a variation to ionosphere also occurred. Especially solar-based magnetic effects cause irregular variations in the ionosphere. For this reason, for the ionosphere related studies, solar and geomagnetic indices such as Kp indice, Dst indice, Solar radio flux and Sunspot number are necessary to specify the solar and geomagnetic disturbance level.

### 3. Modeling the Ionosphere

In recent years, especially after the 1970s, modeling studies of the ionosphere have gained momentum. Various models such as the Bent Ionospheric Model, the Parameterized Ionospheric Model, the NeQuick Model and the International Reference Ionosphere Model are well known global ionosphere models used as reference in many ionospheric studies. These models describe the global behavior of the ionosphere at any location and any time without nearby measurements. But the electron density is quite changeable, they only provide monthly averages of ionosphere behaviour for especially magnetically quite conditions [19]. In this section these models and some particular studies about them are given.

The Bent model was developed by Rodney Bent and Sigrid Llewellyn in 1973 [20] for the satellite tracking satellite intercommunication and corrections of ionospheric delay. The development of the Bent model involved fitting a theoretical electron density profile to a database of ionospheric measurements. This model describes the ionospheric electron density as a function of latitude, longitude, time, season and solar radio flux. With a given location, time and date the Bent model describes the electron density. Its resultant profile is composed of five sections: a bi-parabola, to model the lower ionosphere; a parabola which joins together the top and bottom side ionosphere; and three exponential profile segments which were combined to model the topside ionosphere [21]. Bent model does not include the lower layers (D,E,F1). It uses ionosonde and satellite data.

The Parametrized Ionospheric Model (PIM; [22]), is a climatological global ionospheric and plasmaspheric model based on the parameterized output of several regional theoretical ionospheric models and an empirical plasmaspheric model [23]. It is made up of four different physical models: a low-latitude F layer model, a mid-latitude F layer model, a combined low and middle latitude E layer model and a high latitude E and F layer model. These four models are based on a tilted dipole representation of the geomagnetic field and its corresponding geomagnetic coordinate system [24]. The PIM model produces electron density and ion composition profiles. Detailed information about PIM model is given in Stankov et al. [25].

The International Reference Ionosphere (IRI) model is recommended for international use by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI) mainly used for the specification of ionospheric parameters [26]. For a given location, time and date, IRI describes monthly averages of the electron density, electron temperature, ion temperature, ion composition and ion drift in the altitude range from 50 km to 1500 km. This model is still being developed and up-
dated. The first version of IRI was released in 1978 which was followed by several steadily improved editions in 1986, 1990, 1995, 2001, 2007 and 2012. Besides, IRI 2012 has recently been published on the website (http://iri.gsfc.nasa.gov/). Also there is not any study about IRI 2012 that has been published yet. Detailed information about the 2007 version of the IRI model and evaluation of the model for the European region are given in Bilitza and Reinisch [27] and Maltseva and Poltavsky [28]. Bilitza et al. [29] describe the 2007 version of the model and review efforts towards future improvements, including the development of new global models for the F2 peak density and height, and a new approach to describe the electron density in the topside and plasmasphere. Furthermore, performance analysis of the IRI 2007 and comparison with IRI 2001 is given in Scida et al. [30]. One of the most important data sources for the IRI electron density is the worldwide network of ionosonde stations. Besides the ionosonde, incoherent scatter radars, several compilations of rocket measurements, and satellite data (recently GPS) are used some of the other data sources.

NeQuick is a quasi-experimental model which provides a quick way to estimate electron density. It is developed at the Aeronomy and Radio Propagation Laboratory (ARPL) of the Abdus Salam International Centre for Theoretical Physics (ICTP), Trieste, Italy and at the Institute for Geophysics, Astrophysics and Meteorology (IGAM) of the University of Graz, Austria. For the desired time and place NeQuick model is able to give the electron concentration distribution on both the bottomside and topside of the ionosphere. It is also offered as real time ionospheric correction model for calculating the amount of STEC at ground to satellite or satellite to satellite path for the European Space Agency’s (ESA) Galileo users [31]. Because of the Galileo navigation system is still being developed for the estimations that is made with NeQuick, data of IGS (International GNSS Service) Stations is used [32]. Detailed information can be acquired in [33].

Bilitza et al. [34] compared the Bent model and the IRI model and their application for satellite orbit determination. Because of the more detailed representation of the bottom side density structure IRI showed better results.

The IRI model is however more accurate in predicting the bottom-side ionosphere than the top side ionosphere since it is derived mostly from ionosonde data. To overcome this situation, Okoh et al. [35] additionally used NeQuick model as the top side option for the modeling over Nigeria.

A comparison of the vertical electron content from Bent, IRI and GPS were performed in Meza et al. [21]. In this study a number of quiet geomagnetic days has been chosen because Bent and IRI models were developed to work in these conditions. Results showed that GPS model has the best global VTEC representation at any latitude and longitude when compared to other two models.

For the topside ionosphere NeQuick and PIM model were compared in Stankov et al. [25]. Results of this comparison are analyzed and suggestions are put forward to further improving the models in equation.

Prasad et al. [36] was conducted on the comparison of the GPS-TEC with the IRI-2007 model derived TEC considering three different options (IRI-2001, IRI-2001 corrected and Ne-Quick) available in the model for the topside electron density. Additionally Adewale et al. [37] grouped the VTEC values into four seasons namely March Equinox (February, March, April), June Solstice (May, June, July), September Equinox (August, September, October) and December Solstice (November, December, January). For both study the TEC derived with Ne-Quick and IRI-01 corrected options show better agreement with GPS-TEC while the TEC from IRI-01 method shows larger deviations.

Chauhan and Singh [38] reported that during the daytime GPS-TEC is in close agreement with NeQuick and IRI – corr however corresponding nighttime values are quite close to IRI 2001. In contrast, Sethi et al. [39] showed that over an equatorial station, the agreement between the IRI 01-corr and TEC observations is better during daytime; while outside this time period, NeQuick model reveal better agreement. However Adewale et al. [37] showed that agreement between observed TEC and NeQuick predictions is better during both daytime and nighttime over the equatorial African sector. Chauhan and Singh [38] used data from a low-middle latitude stations in the Indian sector and Sethi et al. [39] used data from only one equatorial station from the Indian sector; however Adewale et al. [37] have used data from thirteen equatorial GPS stations.

4. GPS BASED IONOSPHERE MODELING

GPS use has expanded beyond its initial military oriented purpose since 1993 [40]. The development of the GPS and creation of GPS networks that provide worldwide data availability through the internet opened up a new era for GPS based researches. Recently, the new possibility of estimating the global distribution of free electrons within the ionosphere by means of GPS has opened new perspectives in the field of ionospheric research [41].

4.1 Extracting ionospheric information from GPS observations

Dual-frequency GPS observations can be used to determine slant total electron content (STEC) which is the integral of the electron density along the signal path between the satellite and the receiver. A dual frequency GPS receiver can provide carrier phase and code observations for L1 and L2 with carrier frequency of $f_1$ and $f_2$ respectively. Depending on the total electron content along the signal path from satellite to receiver and signal frequency, ionospheric delay can be expressed as [3, 42],

$$l = \frac{\lambda \text{STEC}}{f^2}$$ (1)
where \( I \) is the ionospheric range delay at frequency \( f \), \( \alpha = 40.3 \times 10^{16} \text{ ms}^{-2} \) TECU\(^{-1} \) (1 TECU = 10\(^{16}\) el./m\(^2\)) is a constant value used to convert from TECU to length units. In this equation, only the first order delay expressed in length unit is given, whereas higher order and bending effects are neglected. Ionospheric range delay is negative for carrier phase measurements and positive for pseudorange measurements.

The geometry free linear combination of GPS signals, is generated by subtracting simultaneous pseudorange \((P_1 - P_2)\) or carrier phase observations \((\phi_1 - \phi_2)\). This is also referred to as L4 combination. With this combination, the satellite-receiver geometrical range and all frequency independent biases \( (\text{e.g., clock error, tropospheric delay, etc.}) \) are removed [43].

\[
\phi_4 - \phi_1 - \phi_2 - \alpha \cdot \text{STEC} \cdot \left( \frac{1}{f_1^2} - \frac{1}{f_2^2} \right) = \lambda_1 N_1 - \lambda_2 N_2 + b_x + b_y + \varepsilon \phi \quad (2)
\]

In this equation, \( \phi_4 \) is the carrier phase measurement; \( \lambda_1 \) and \( \lambda_2 \) are the wavelengths of the L1 and L2 carriers; \( N_1 \) and \( N_2 \) are integer carrier-phase ambiguity terms for L1 and L2 respectively; \( b_x \) and \( b_y \) are the so-called inter frequency biases on carrier phase measurements and \( \varepsilon \phi \) is the effect of noise and multipath.

In the geometry free linear combination for pseudorange observations; which is written in eq. (3), \( P_4 \) is the geometry free linear combination of pseudorange observations; \( b_x \) and \( b_y \) are inter frequency biases on pseudorange measurements and \( \varepsilon_p \) is the noise and multipath effects in \( P_1 \) and \( P_2 \).

\[
P_4 = P_1 - P_2 = \alpha \cdot \text{STEC} \cdot \left( \frac{1}{f_1^2} - \frac{1}{f_2^2} \right) + b_x + b_y + \varepsilon_p \quad (3)
\]

STEC can be acquired from carrier phase or pseudorange observations by extracting it from Eq. (2) or Eq. (3) respectively. The code derived STEC however, is corrupted by a high level of noise factors including multipath effects and random measurement noise. The phase derived STEC is also corrupted by these factors, but to a much lesser extent. However, due to the ambiguous integer bias terms, which are the unknown number of whole cycles of the carrier signal from satellite to the receiver, the phase derived STEC is a relative value. To deal with the drawbacks inherent in STEC estimates derived separately from code and phase measurements and also in order to make use of their superiority, one way is to combine these measurements. The basic idea of this, referred to as a smoothing technique, is to smooth the noisy code derived STEC with the precise phase derived relative STEC. For this propose several methods have been proposed. An algorithm of smoothing code pseudorange measurements using carrier phase was first investigated in Hatch [44]. Besides this, Springer [45] proposed another method for smoothing. However in these methods pseudorange observations are smoothed by its corresponding carrier phase observation individually. But, as STEC is obtained from the geometry-linear combination of GPS observations, an algorithm to smooth the pseudorange ionospheric observable eq.(3) should be more appropriate for ionosphere modeling studies. For this purpose, Ciraolo et al. [43] presented an algorithm for the smoothing the pseudorange observables, which known as "carrier to code leveling process". With small modification of the algorithm presented by Nohutcu et al. [42] is explained below.

With the combination of Eqs.(2) and (3) for an observation following equation is obtained:

\[
P_4 + \phi_4 = \lambda_1 N_1 - \lambda_2 N_2 + B_R + B_S + b_x + b_y + \varepsilon_p \quad (4)
\]

The noise and multipath term for pseudorange observation, \( \varepsilon_p \), is around 100 times greater than for carrier-phase observations [46]. For this reason, the noise and multipath term for carrier phase observations, \( \varepsilon_L \), has been neglected. In Eq. (4), the ambiguity terms \( N_1 \) and \( N_2 \) are remain constant for every continuous arc which defined as the group of consecutive carrier-phase observations without discontinuities. Inter frequency terms are stable for periods of days to months, as well as they can be treated as constants for a continuous arc [47]. Therefore Eq. (4) should provide stable results and an average value \( \langle P_4 + \phi_4 \rangle_{\text{arc}} \) can be computed for a continuous arc as follows:

\[
\langle P_4 + \phi_4 \rangle_n = \frac{1}{n} \sum_{i=1}^{n} (P_4 + \phi_4) = \langle \lambda_1 N_1 - \lambda_2 N_2 \rangle_n + B_R + B_S + b_x + b_y + \langle \varepsilon_p \rangle_n \quad (5)
\]

where \( n \) is the number of measurements in the continuous arc. With the subtraction of Eq. (3) from Eq. (5) ambiguity terms are eliminated.

\[
P_i = \langle P_4 + \phi_4 \rangle_n - \phi_1 = \alpha \cdot \text{STEC} \cdot \left( \frac{1}{f_1^2} - \frac{1}{f_2^2} \right) + b_x + b_y + \langle \varepsilon_p \rangle_n - \varepsilon \phi \quad (6)
\]

where \( P_i \) is the carrier phase smoothed pseudorange ionospheric observable. Thus STEC can be acquired in TECU by

\[
\text{STEC} = \left( P_i - b_x - b_y - \langle \varepsilon_L \rangle_n + \varepsilon \phi \right) \cdot \left( \frac{40.3(f_1^2 - f_2^2)}{f_2^2 - f_1^2} \right) \quad (7)
\]

### 4.2 GPS-based modeling studies

STEC data obtained from accurate GPS observations resulted in numerous GPS-based ionosphere modeling studies. All proposed GPS-based ionospheric models could be classified into two models, regional and global models as
these models are derived from a data set collected in the corresponding region. Regional TEC models usually have better mapping accuracy because of dense station coverage in the regional GPS networks. Regional TEC models can mainly be divided into two different categories: grid-based and function based [48]. The grid-based model, such as the SBAS (Satellite-Based Augmentation System), first proposed by the MITRE Corporation and the Air Force Phillips Laboratory [49, 50] while the function based model is based on mathematical functions; for example, the polynomial model [24, 51], the low-degree spherical function model [52] as well as the triangle series model [53, 54]. These three mathematical function-based models have been investigated and compared in Liu et al. [55]. However, the long term TEC predictability is very important especially for navigation and space applications, regional models are the lack of long-term TEC predictability. Unlike regional models, Global models such as the KLOBUCHAR model and the global ionosphere map (GIM) model support global TEC prediction [56].

Spherical harmonic model is generally used to model the Global Ionosphere. Based on this model spherical cap harmonic model for regional ionospheric modeling is used by many researchers. Liu et al. [56] and Liu et al. [57] are two of them. Liu et al. [56] investigated the usability of spherical cap harmonic model for mapping and predicting the regional TEC values. Its approach resembles the one using spherical harmonic functions in the global case; however, the mathematical fundamentals are different. Liu et al. [57] applied this model for high latitudes and Arctic region and also compared the results with some regional models. The results demonstrated that the spherical cap harmonic model has a comparable mapping accuracy compared to other regional TEC approaches; Polinomial, Triangular series and Lower degree spherical function models.

There are many centers and universities where Global Ionospheric Maps (GIMs) are generated by ionospheric groups. JPL (Jet Propulsion Laboratory), CODE (Center for Orbit Determination in Europe), IGS (International GNSS Service), NOAA (US National Oceanic and Atmospheric Administration), UNB (University of New Brunswick), ESA (European Space Agency), UPC (Polytechnical University of Catalonia) are some of them. In the early years different GIMs presented significant total electron content (TEC) biases which made difficult to combine them into a common product. Then, with the realization of independent updates of techniques by different centers it was made possible to combine the different GIM since due to their increased compatibility level [58]. Detailed information about Ionospheric modeling techniques of JPL, CODE, NOAA and IGS working groups are given in Liu et al. [59].

No matter whether it is function or grid-based, for two dimensional (2D) ionosphere model STEC values are usually converted to height independent VTEC values by introducing mapping functions. Different ionospheric mapping functions, SLM (Single Layer Model; for different altitudes), Chapman profile, Broadcast model and Q-factor, which can be used for this purpose, were analyzed and their superiority was questioned in Schaer [47] and found that in practice the SLM mapping function is mostly used. In the single layer model, all electrons in the ionosphere are assumed to be contained in a shell of infinitesimal thickness. The height of this idealized layer approximately located at the altitude of between 350 and 450 km where the electron density is maximum. In fact, this assumption is only an approximation to the real physical truth since the ionosphere is located approximately at an altitude of 50 km to 1000 km above Earth’s surface. The ionosphere zone and single layer model are illustrated in Fig. 2.

In Fig. 2, the ionospheric pierce point (IPP) is the intersection of the single layer shell and the path of the GPS signal; R is the mean earth radius, H is the single layer height, whereas z and z’ stand for the satellite zenith angle at the receiver and IPP respectively. Based on the figure, STEC can be converted height independent VTEC by means of eq. 8 and 9.

\[ F(z) = \frac{\text{STEC}}{\text{VTEC}} = \frac{1}{\cos z} \]  
\[ \sin z' = \frac{R}{R + H} \sin z \]

The main shortcoming of the two dimensional model (2D) is known to be its inability to express the vertical profile of the ionosphere. Therefore, in order to improve the accuracy of the ionosphere estimates and to monitor the temporal ionosphere variations, the single layer model should be expanded to multi-layer ones. For this propose ionospheric tomography modeling has been proposed and started to receive more attentions.

Austen et al. [60] was the first to apply the tomography technique to ionospheric imaging. Then extensive studies have been performed on this topic. Some of them are reviewed by; Austen et al. [61], Raymund [62], Ray-
mend et al. [63], Raymund et al. [64], Fremouw et al.[65], Kersley et al.[66], Howe et al. [67], Liu and Gao [68], Liu and Gao [69], Lee et al. [70].

In a three dimensional (3D) ionosphere model utilizing the tomography technique, STEC measurements are inverted into electron density distribution, based on latitude, longitude and height. Although the ground based GPS receivers provide relatively accurate STEC, such data cannot provide adequate vertical resolution for ionospheric tomography as they scan the ionosphere by vertical or near-vertical paths [71, 72]. In order to provide relative sensitivity for the vertical structure of the ionosphere, additional data sources, such as ionosondes, satellite altimetry or GPS receivers on Low-Earth-Orbiting (LEO) satellites were considered in many ionosphere based studies [72-77]. Tomography is a two-step process. In the first step, integral measurements are made of the medium of interest, ideally along many paths at many different viewing angles. In the second, these integral measurements are inverted to obtain an estimate of the field [67]. The methodology of 3D modeling is given by Liu and Gao [69].

Gao and Liu [48] compared the 2D grid-based and 3D tomography-based ionosphere modeling results using regional GPS network data. Data analysis indicated that modeling accuracy based on the tomography method is much higher than 2D grid based approach.

Liu et al. [78] demonstrated the ionosphere tomographic modeling performance using GPS data during the geomagnetic storm event. In this study, the short term prediction of TEC was performed for 3 geomagnetic storm days by using dual frequency GPS receivers. In the case of less disturbed conditions, about 80% of STEC was recovered by the model prediction. But during extreme ionospheric storm period (Kp=9) this rate is quite low.

Liu and Gao [3] investigated the ionospheric total electron content (TEC) predictions using a multiple layer tomographic method over a local GPS network. With this study it is confirmed that the short term TEC predictions generated from the ionospheric tomography model could recover about 95% of the total ionospheric TEC and can be used by single frequency GPS receiver users to eliminate the majority of the ionospheric effects for improved positioning.

Yin et al. [79] and Pokhotelov et al. [80] used ionospheric tomography to image the ionosphere over the polar area during a disturbance period in October 2003. The density of GNSS receivers in the polar area is low resulting into a small scale identification of ionospheric structures difficult while the ionospheric structures can change at high velocities. They solved this by incorporating a-priori knowledge of plasma motion into the inversion procedure.

Brunini et al. [8] presented a methodology for two-dimensional and three dimensional global ionospheric modeling and pointed out the advantages of GPS for the modeling.

Beyond 3D (depending on latitude, longitude and height) tomography modeling, the consideration of time 4D tomographic modeling approach is used in many studies. Four-dimensional simulations of tomography system based on data from the Global Positioning System and a low Earth-orbiting satellite were reported in Howe at al. [67]. Allain and Mitchell [81] presented a comparison about 4D tomographic mapping with thin shell approximation. A comprehensive review of ionospheric 2D, 3D and 4D tomographic approaches with its history, current state and future directions are given by Bust and Mitchell [82].

In order to produce an ionosphere image over Scandinavia in December 2006, Van de Kamp [83] used 4 dimensional tomography using TEC measurements from the dense Geotrim GPS network in Finland, and inversion using the software package MIDAS. The results have been tested by comparing with – Geotrim TEC measurements calibrated independently; -EISCAT incoherent scatter radar returns from Tromsø; -FORMOSAT3/COSMIC radio occultation measurements. These comparisons show the general good performance of the procedure.

In recent years, interpolation techniques are commonly used for regional and global modeling of the ionosphere based on GPS observations. Foster and Evans [84] investigated the possible interpolation techniques for reconstructing ionospheric TEC maps.

Wielgosz et al. [85] showed that kriging and multi-quadratic interpolation/prediction techniques can be used regional ionosphere mapping when compared with International GNSS service (IGS) Global Ionosphere Maps (GIMs). The usability of kriging technique for the improvement of Global ionospheric maps in the case of Technical University of Catalonia (UPC) indicated by Oru’s et al. [58]. Different from the kriging and multi-quadratic interpolation techniques, performance of the Thin Plate Spline Interpolation technique for ionosphere modeling particularly during geomagnetic storm period was investigated by Moon [86].

Nohutcu et al. [42] proposed two approaches (2D and 3D) to model the Vertical Total Electron Content (VTEC) of the ionosphere with quadratic B-Spline functions. For the 2D case VTEC is modeled in a sun-fixed reference frame. In the 3D approach, the 2D model is extended to represent the temporal variations in an Earth-fixed reference frame. Results indicate that the 3D solutions represent the temporal change in the ionosphere more successfully than the 2D solutions.

Durmaz et al. [87] presented a new approach for regional spatio-temporal mapping of VTEC in three dimensions in terms of latitude, longitude and time using Multi-variate Adaptive Regression Splines in a sun fixed system.

In addition to these interpolation techniques, Neural Networks (NN) methods are used in ionospheric studies involving TEC modeling using GPS data. Detailed information about NN approach by using GPS data is given by Hernandez et al. [88]. Leandro and Santos [89] performed a study for testing NN’s performance at low and high
solar activity periods by using GPS data. Analyses of the results indicated that NN model is capable of recovering, on average, 85% of TEC values. Comparison of NN model and IRI model was investigated in Habarulema et al. [90]. Comparison was performed by using GPS data and it revealed that the IRI provides more accurate predictions than the NN model during spring equinox. However, on average the NN model predicts TEC more accurately than the IRI model. Habarulema et al. [91] investigated whether the NNs can be used to follow the TEC dynamics during magnetic storms. Results show that NNs are appropriate for predicting TEC variations during disturbed conditions; also, the accuracy of both the NN model and IRI-2007 model is highly comparable in the early morning hours than in the late evening hours during the storm. Gurun et al. [92] also investigated the two NN methods, Multilayer Perceptron (MLP) and Radial Basis Networks (RBN), in terms of their performance and superiority to each other for regional ionosphere mapping.

GPS-based models which are mentioned above are not supported with related software accessible to scientific community. For this reason, researchers who want to use one of these models to ground based GPS data should need to prepare the software codes required. But this is not so easy. Exceptionally, Bernese GPS software, developed by Astronomical Institute of University of Bern, can be used for this purpose. However it is only use spherical harmonic expansion to represent VTEC regionally or globally.

5. SUMMARY AND CONCLUDING REMARKS

The variant effects of ionosphere around the globe have made ionospheric modeling a necessity. The development of GPS and its ability to provide accurate ionospheric information has increased its popularity in this field.

The structure of ionosphere carries great importance for its modeling. In different ionosphere regions and different layers, ionosphere density shows big changes when the ionospheric disturbance effects are taken into consideration. The causes of these changes and the criteria which show the changes are given in the second part.

In the third part, some brief information about various ionosphere models such as Bent Ionospheric Model, the Parameterized Ionospheric Model, the NeQuick Model and the International Reference Ionosphere Model is given. In these models GPS observations can be used as data sources. Models’ performance comparisons are generally rely on GPS based VTEC representation which is considered as being reliable. Particularly IRI model has performed big progress for the last ten years. For the IRI model, GPS is a promising new resource for improvements of the model as well as an excellent candidate for data assimilation into the IRI model. However, all models provide monthly averages of ionosphere behaviour for especially magnetically quite conditions.

In the fourth section, it is mentioned that the role of the GPS on the modeling of ionosphere is the main purpose of this study. In some studies GPS data are used as a single data source, for others form an additional data source. For instance, in GIM or interpolation based modeling applications it is used as a single data source, however in tomography or NN models it is used as an additional one. One of the reasons is the dimension concept which is crucial for data selecting. For example, though ground based GPS receivers provide relatively accurate STEC, these data can not provide adequate vertical resolution for some models (e.g. tomography); hence additional data sources are needed.

Finally, ionospheric models based on GPS data can be used for different applications, such as space weather events, empirical model predictions, and user navigation improvement. The worldwide IGS network offers a unique opportunity to extract information about the Earth's ionosphere and provide valuable GNSS data for monitoring and mapping the ionosphere.

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