IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received August 28, 2020, accepted September 15, 2020, date of publication September 18, 2020, date of current version October 1, 2020.
Digital Object Identifier 10.1109/ACCESS.2020.3024920

Performance Evaluation of Adjusted Spherical Harmonics Ionospheric Model Over Indian Region

KONDAVEETI SIVA KRISHNA, DEVANABOYINA VENKATA RATNAM, (Senior Member, IEEE), MIRIYALA SRIDHAR, (Senior Member, IEEE), P. BABU SREE HARSHA, (Graduate Student Member, IEEE), AND GAMPALA SIVAVARAPRASAD, (Member, IEEE)
Department of Electronics and Communication Engineering, Koneru Lakshmaiah Education Foundation, Vaddeswaram 522502, India

Corresponding author: Devanaboyina Venkata Ratnam (dvratnam@kluniversity.in)

This work was supported in part by the Project Development of Single Frequency Ionospheric Correction and Plasma Bubble Detection Algorithms Using GPS Aided GEO Augmented Navigation (GAGAN) and Navigation Indian Constellation (NavIC) Total Electron Content Observations Sponsored by NavIC–GAGAN Utilization Program, Space Applications Centre, Ahmedabad, India, under Grant NGP-10, and in part by the Research Projects Science and Engineering Research Board (SERB) through the Vide Sanction Order, Government of India, under Grant ECR/2018/001701.

ABSTRACT The ionosphere is perceived to be a predominant source of ranging error of Global Navigation Satellite System (GNSS) signals to degrade the positional accuracy. The suitable ionospheric model is necessary to improve the positional accuracy of GNSS and Satellite-Based Augmentation System (SBAS) users. In this paper, the regional ionospheric model (RIM) over the Indian region is implemented based on the adjusted spherical harmonics function (ASHF) model from dense GPS TEC stations over the Indian region. Also, the evaluation of the different ASHF order models conducted to identify the proper order of the ASHF model for Indian low latitude ionospheric calm and adverse space weather conditions. The results confirm that the 4th order ASHF ionospheric model can identify the northern Equatorial Ionization Anomaly (EIA) TEC crest patterns over the Indian region. The comparison of the 4th order ASHF ionospheric model carried out with dual and single frequency ionospheric models like as Klobuchar model, Centre for Orbit Determination in Europe (CODE) Klobuchar model, NeQuick G model, BeiDou System (BDS2) model and CODE Global Ionospheric Maps (GIM) models. The outcome of the results indicates that the 4th Order ASHF ionospheric model would be potential for single and dual-frequency ionospheric models for GNSS and SBAS systems.

INDEX TERMS Ionosphere, total electron content (TEC), GPS aided GEO augmented navigation (GAGAN), adjusted spherical harmonics function (ASHF).

I. INTRODUCTION

The regional ionospheric Total Electron Content (TEC) model is necessary for High Frequency (HF), communication, and navigation applications to characterize local spatial-temporal and dispersive properties of the ionosphere [1]. The primary ionospheric parameter known as Total Electron Content (TEC) can be measured using dual-frequency Global Navigation Satellite System (GNSS) receivers. The single and dual-frequency ionospheric models are mandatory components to improve the positional accuracy of GNSS and its satellite and ground-based augmentation navigation systems [2]. The range delay errors introduced in the GNSS and SBAS are highly variable and least predictable, especially in equatorial and low latitude regions due to Equatorial Ionization Anomaly (EIA) [3]. Klobuchar [4] proposed an empirical-based ionospheric broadcast model popularly known as Klobuchar ionospheric model for single-frequency GPS receivers. Klobuchar model is more straightforward and requires eight broadcasting coefficients in the navigation message of GPS satellites to compute ionospheric corrections. However, Klobuchar ionospheric model can predict 50% of actual ionospheric delays over the mid-latitude region and low latitude regions [5], [6]. The major

The associate editor coordinating the review of this manuscript and approving it for publication was Yue Zhang.

drawback of the Klobuchar ionospheric broadcast correction model is its inability to model night-time ionospheric variability due to constant offset value (5 nanoseconds). The Russian GLONASS navigation system does not equip with a single frequency ionospheric model [6]. NeQuick model requires three ionospheric broadcast coefficients which will be sent to Galileo users as part of the navigation message to represent global ionospheric behavior [7], [8]. NeQuick G model performance is better than the Klobuchar model [9]. BeiDouglobal broadcast ionospheric delay correction model (BDGIM) is developed for the BeiDou-3 navigation system [10].

BDGIM model computes ionospheric time delay using nine BDS GIM coefficients based on the modified spherical harmonic function model formulation [11]. The long-term performance analysis of the global BDGIM ionospheric model is still in the process. Indian regional navigation system called as Navigation with Indian Constellation (NAVIC) adopted Klobuchar and ionospheric grid corrections for single-frequency NAVIC users [12]. The Klobuchar ionospheric model is adopted for single frequency Japan's Quasi-Zenith Satellite System (QZSS) [1].

The Centre for Orbit Determination in Europe (CODE) has been providing Global Ionospheric Maps (GIM) with 1-hour resolution for single-frequency GNSS ionospheric delay corrections [2]. The Klobuchar like coefficients have been routinely estimated using GIM TEC maps and found that the CODE Klobuchar model with eight coefficients is better than Klobuchar model [13]. Hence, GNSS single frequency users require higher prediction accuracy in ionospheric delay estimation for positioning applications.

On the other hand, satellite-based augmentation systems (WAAS-USA, EGNOS-Europe, QZSS-Japan, GAGAN-India) adopted dual-frequency ionosphere models to provide ionospheric differential corrections and their error bounds via GEO stationary satellites. The user SBAS receiver then interpolates the ionospheric delay from surrounding four Ionospheric Grid Points (IGPs) using the Bi Linear interpolation algorithm [14]. Large temporal and spatial gradients in the ionospheric delays are significant in the equatorial and low latitude regions [15], [16]. A regional ionospheric TEC model is necessary for modeling TEC data scattered over the region of interest [17]. SBAS Ionospheric Grid-based models are generally used to estimate the ionospheric delays at the predefined ionospheric grid points and provide the values to the users [18]. Indian Satellite-based Augmentation system - GAGAN system adopted the ionospheric grid model based on a multilayer Data Fusion model developed by the Indian Space Research Organization (ISRO) [19]. However, none of these SBAS models provide model coefficients that are to be transmitted by GNSS satellites as a part of the navigation message.

Ratnam and Sarma [20] have implemented the regional ionospheric TEC model based on third-order spherical harmonic function (SHF) with 16 model coefficients. However, SHF ionospheric model produces smoother variations as compared to other ionospheric grid models over the Indian region [20]. An extended single layer model (ESLM) mapping function was implemented to eliminate ionospheric mapping error for the conversion of vertical TEC from slant TEC as part of the SHF ionospheric model [21]. Dabbakuti *et al.* [22] implemented the Adjusted Spherical Harmonics Function model for few ionospheric grid locations with 17 GPS TEC stations data of the 2004 year. The order suitability of the ASHF model yet to be investigated for low latitude ionospheric conditions. The suitability of the regional ASHF ionospheric model as a single frequency ionospheric broadcast model to be tested over low latitude ionospheric conditions. In this paper, an attempt has been made to identify suitable order adjusted spherical harmonic function models and 25 model coefficients for both single and dual-frequency GNSS users. The proposed model has well captured the EIA features under adverse space weather conditions.

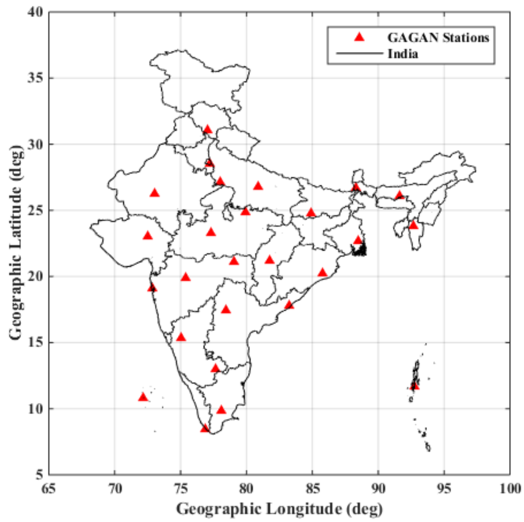

FIGURE 1. The distribution of the 26 reference GPS continues mentoring stations.

II. METHODOLOGY

Airports Authority of India (AAI) and Indian Space Research Organization (ISRO) operating 26 GPS TEC stations under the GPS Aided Geo Augmented Navigation (GAGAN) TEC network over the Indian region (Fig. 1). This GAGAN network of 26 GPS dual-frequency receivers being a part of Space-Based Augmentation System (SBAS) program are useful to monitor and model the ionospheric TEC conditions. These 26 GPS dual-frequency receivers will provide the SBAS ionosphere differential corrections over the Indian region. The GPS TEC observations like slant TEC (STEC), GPS week, GPS time, PRN number, elevation angle, azimuthal angle information from all the GPS network receivers (Manufacturer: Novatel, Model: GSV4000B) over India are considered. The Receiver Independent Exchange (RINEX) format of the GPS receivers provides all STEC observations using code combined with carrier pseudo-range measurements with a 1-min time resolution. Kalman filter estimation procedure was used to remove the satellite and receiver instrumental biases [23]. VTEC values are calculated from STEC measurements based on elevation-dependent mapping function, assuming the thin shell height of the ionosphere as 350 km [24], [28], [29]. The corresponding ionospheric pierce point latitude and longitudes of all satellites concerning GPS stations are computed. In order to avoid multipath effects on GPS signals, the elevation masking angle is considered as 40° [28], [29]. GPS-TEC data from 26 locations over the Indian region is considered during March, June, September, and December 2015 year to evaluate the performance of selected ionospheric models. The data collected for these seasons ASHF model estimates ionospheric delay using the Fourier series expansion method with the sum of latitudinal Legendre function and longitudinal sine and cosine terms. The mathematical expression for mapping the regional vertical total electron content (VTEC) using the adjusted spherical harmonics function (ASHF) model is given by [25].

$$
\begin{aligned}
I_v(\phi_r, \lambda_r) &= \sum_{n=0}^{n}\sum_{m=0}^{m}(M(h_{iono}, el) \\
&\quad \times \left[\overline{P_{nm}}\cos(\phi_r)\{C_{nm}\cos(m\lambda_r) + S_{nm}\sin(m\lambda_r)\}\right]) \\
\phi_r &= \frac{\pi}{2} - \frac{\pi}{\theta_{\max}}\left[\frac{\pi}{2} - \arccos(\sin\phi_0 \cdot \sin\phi_r \right. \\
&\qquad \left. + \cos\phi_0 \cdot \cos\phi_r \cdot \cos(\lambda_r - \lambda_0)\right] \\
\lambda_r &= \arcsin \\
&\quad \times \left[\frac{\sin(\lambda_r - \lambda_0)\cdot\cos\phi}{\arccos(\sin\phi_0\cdot\sin\phi_r + \cos\phi_0\cdot\cos\phi_r\cdot\cos(\lambda_r-\lambda_0))}\right]
\end{aligned} \tag{1}
$$

where $M(h_{iono}, el) = \left[1 - \left[\frac{\cos(el)}{1+\frac{h_{iono}}{R_e}}\right]^2\right]^{1/2}$

$M(h_{iono}, el)$: mapping function
el : satellite elevation angle
R_e : represents earth radius (6378 km)
h_{iono} : thin shell height from the earth (350 km)
m and n: order and degree
ϕ_r and λ_r: adjusted latitude and longitude of the IPP
ϕ_0 and λ_0: geographic latitude and sun-fixed longitude
$\theta_{\max}$: half-angle of the spherical cap coordinate system
C_{nm} and S_{nm}: ASHF model coefficients to be estimated using regional GPS-TEC data
P_{nm} : normalized associated Legendre functions.

The ASHF approach includes a surface model is characterized by the order of expansion m = 2, 3, 4, 5,6, 7, 8, 9, 10 including the coefficients n = 4, 9, 16, 25, 36, 49, 64, 81, 100 respectively. The order and degree of ASHF model describe the resolution of the model, and it depends upon the region and the number of measurements.

The Legendre function P_{nm} is given by [26],

$$
\overline{P_{nm}}(\cos f_r) = \begin{cases} (-1)^m\sqrt{\left(n+\frac{1}{2}\right)\times(n-m!)\big/(n+m!)} \\ \times P_{nm}(\cos f_r) & \text{if } m>0 \\ \sqrt{\left(n+\frac{1}{2}\right)}\times P_n(\cos f_r) & \text{if } m=0 \end{cases} \tag{2}
$$

The measurements of the spherical harmonic's expansion Eq. (1) is re-organized in matrix notations as given in below Eq. (3).

$$
Y = \begin{bmatrix} I_{v,1} \\ I_{v,2} \\ \vdots \\ I_{v,k} \end{bmatrix} = H \times x \tag{3}
$$

where,

$$
\begin{aligned}
H &= \left[\overline{\mathrm{P}}_{\mathrm{nm}}(\cos\theta)\{\cos(\mathrm{m}\lambda)\}, \overline{\mathrm{P}}_{\mathrm{nm}}(\cos\theta)\{\sin(\mathrm{m}\lambda)\}\right]_{m\times n} \\
x &= \{C_{\mathrm{nm}}, S_{nm}\}^T
\end{aligned}
$$

The ASHF model coefficients are valid over the geographical area of interest to compute regional ionospheric delay, in turn, represent regional ionospheric behavior.

III. RESULTS AND DISCUSSIONS

To evaluate the suitability order of the ASHF model, 26 GPS TEC stations data during March, June, September, and December 2015 are utilized. Klobuchar, CODE Klob, and BDS-2 model coefficients downloaded from the web (*cddis.gsfc.nasa.gov/pub/gps/data/daily/2015/brdc, ftb://ftp.gipp.org.cn/product/brdion/2015*). ASHF model coefficients are obtained for orders 2, 3, 4 and 5. The spatial resolution is 1° × 1° and temporal resolution is 1 hour for the ASHF model. The 1° × 1° spatial variations of ionospheric TEC values measured from GNSS measurements distributions are discussed in [30]. However, when comparing the performance of the ASHF model with global models, the spatial resolution of the ASHF model was chosen as 5° × 5°. The planetary Kp-index values are available from NOAA (*www.swpc.noaa.gov*). The maximum Kp-index value of 2.3 is observed on 05 March, indicating the geomagnetic quiet day conditions. On 17 March, Kp-index values are more than 7 for most of the time, which clearly depicts the severity of the geomagnetic storm.

Fig. 2 and Fig.3 show the ionospheric TEC maps generated based on ASHF model for orders 2 to 5 with 1° × 1° spatial resolution for 0-23 hours (1-hour temporal resolution) during 05 March 2015 and 17 March 2015. The latitudinal variability (5-40°N) of ionospheric TEC variations captured for all orders of the ASHF model over the Indian longitudes. The EIA crest TEC structures are noticed for geographical longitudes of 70°E, 80°E, 90°E, 100°E on ionospheric quiet day conditions (0<Kp<3) of 05 March 2015 and on

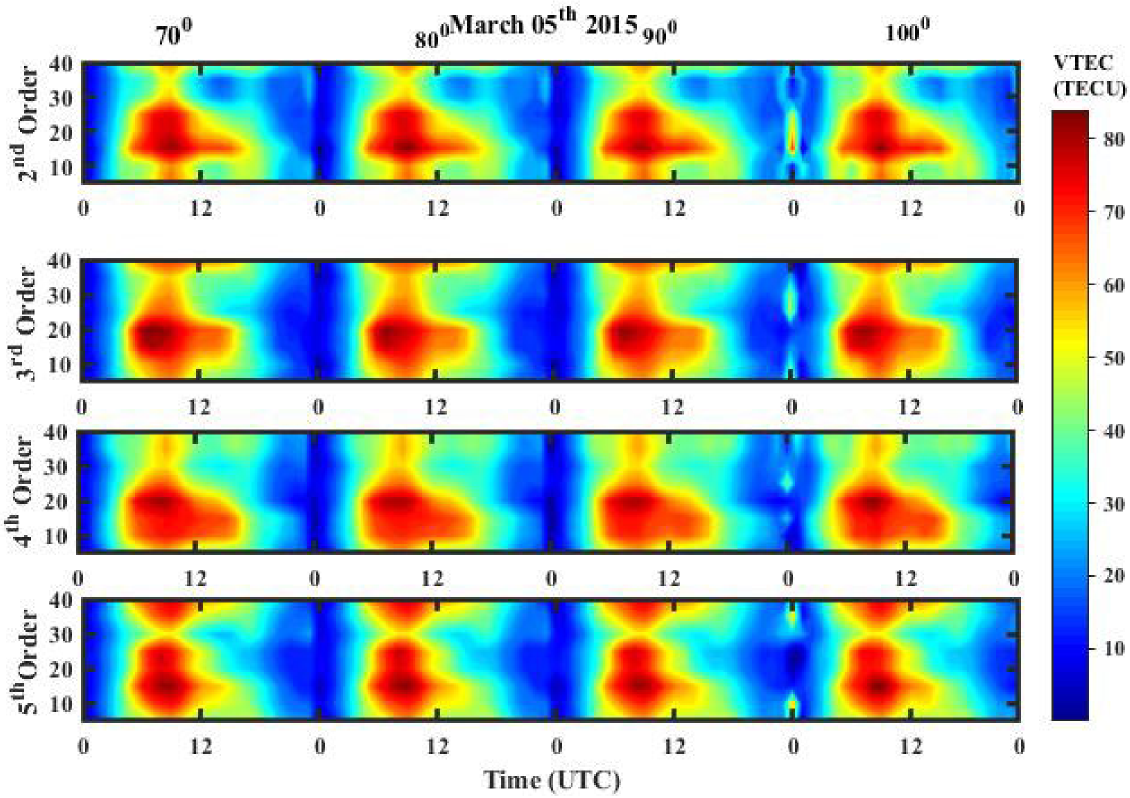

FIGURE 2. EIA peak recognition at 70°E, 80°E, 90°E, 100°E longitudes on geomagnetic quiet day 05-03 2015.

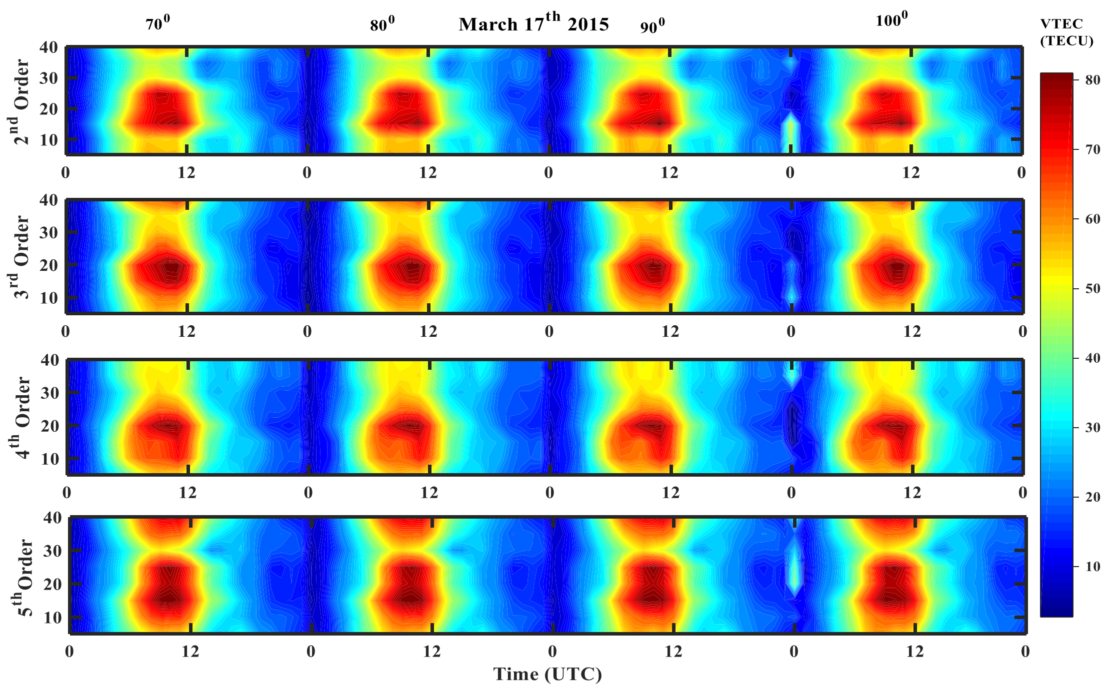

FIGURE 3. EIA peak recognition at 70°E, 80°E, 90°E, 100°E longitudes on geomagnetic disturbed day17-03-2015.

the geomagnetic storm day (4<Kp<9) of 17 March 2015. The peak TEC distributions of 4th order ASHF model for geographical longitudes, 70°E, 80°E, 90°E, 100°E observed with maximum TEC appears near the equatorial low latitude regions with the with a peak of TEC diurnal variations at 14:00 LT. Also, the equatorial ionization anomaly (EIA)

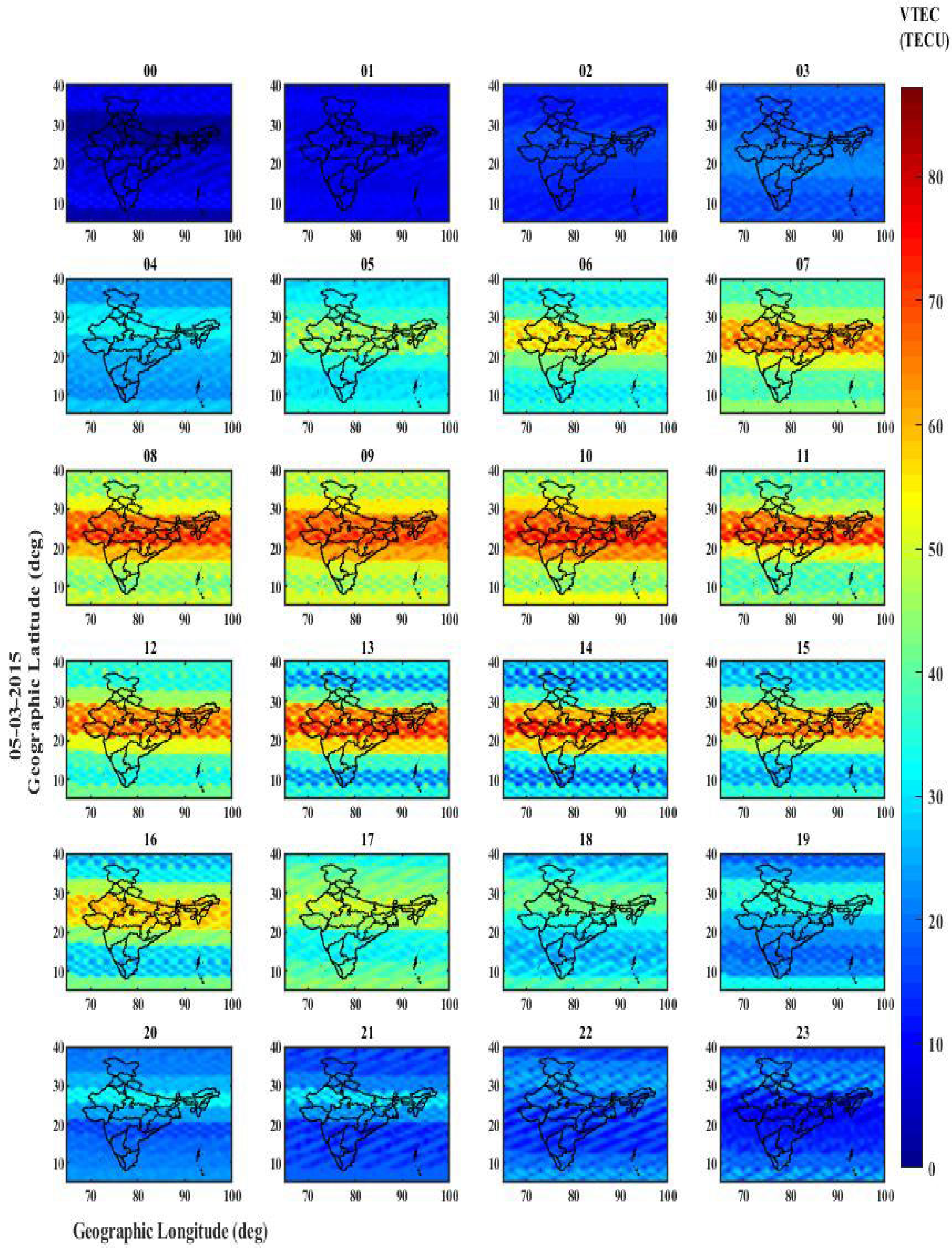

FIGURE 4. ASHF 4th -order TEC results for geomagnetic quiet day 05 March 2015.

phenomenon can be observed apparently in low-latitude regions (15-20°N), during 10:00 and 13:00 LT (IST=UTC+ 5hrs:30 min) for 4th order ASHF model during both geomagnetic quiet and disturbed days (Fig. 2 and 3). The temporal and spatial variations of ionospheric TEC values measured from GPS measurements and the TEC peak

TABLE 1. **The comparison of various orders performance for ASHF model during geomagnetic and distrubed days over indian regions.**

Day	05-March-2015 (Geomagnetic quiet day)				
Statistical Parameter	Max. (TECu)	Min. (TECu)	Mean (TECu)	Std. (TECu)	RMSE (TECu)
Observation data	62.20	9.68	33.51	18.00	----
Order 2	73.82	5.12	35.18	22.94	12.13
Order 3	72.10	3.96	40.54	23.04	13.12
Order 4	66.63	6.52	33.18	17.45	10.00
Order 5	74.05	-0.65	40.44	23.69	13.23
Day	17-March-2015 (Geomagnetic disturbed day)				
Statistical Parameter	Max. (TECu)	Min. (TECu)	Mean (TECu)	Std. (TECu)	RMSE (TECu)
Observation data	66.05	7.44	30.78	19.87	---
Order 2	73.82	5.12	35.18	22.94	11.25
Order 3	73.74	4.70	35.41	22.73	9.56
Order 4	69.45	6.40	32.43	21.50	6.73
Order 5	72.54	-5.80	34.87	23.23	12.45

capture both ionospheric quiet and disturbed EIA characteristics.

distributions discussed in [31]. Whereas an unusual EIA peak distribution could be observed for the 2nd, 3rd, and 5th order ASHF models with the peaks extend from 10°N to 30°N during 05 March 2015 (Fig. 2). Moreover, during geomagnetic disturbed day, 17 March 2015, except for the 4th order ASHF model, for the remaining orders, the ASHF TEC distributions are comparatively uneven with respect to the temporal and spatial TEC distributions (Fig. 3). Hence, 4th order ASHF model is considered as a RIM model over the Indian region due to the low statistical error values recorded for this order as shown in Table 1. Table 1 shows the comparison of maximum, minimum, mean, standard deviation, and the RMSE values of the ASHF model for the different orders (2nd, 3rd, 4th, and 5th orders) considered in the present analysis over Indian region. It is evident from the observations that the proposed 4th order ASHF model has less RMSE and reasonable statistical values when compared with observed data over the Indian region during both the geomagnetic quiet and disturbed days (5-03-2015 and 17-03-2015).

The 4th order ASHF model considered for further analysis. The hourly VTEC maps obtained from the 4th order ASHF model for different latitudes and longitudes covering the entire Indian region using 26 GPS TEC stations on quiet and disturbed days of March 2015. Fig. 4 and Fig.5 illustrate the behavior of the EIA TEC structure for two days (5th March 2015 and 17 March 2015). The X-label gives the geographic longitude (deg) and Y-axis is the geographic latitude (deg), and each panel is in time (UTC). The color bar shows the VTEC values. The typical ionospheric TEC diurnal patterns well represented hourly TEC variations for quiet day conditions (05 March 2015). The entry formation of EIA TEC structures noticed at 6.00 hrs. UTC (11.30 local time) with maximum TEC of 40 TECU. The complete EIA occurred at 9.00 hrs UTC (14.30 local time) with maximum TEC (80 TECU) around 20° N latitudes (Fig.5).

The enhanced EIA TEC structures are noticed from 07.00 to13.00 hrs UTC between the latitude range of 10° to 20° degrees. The maximum TEC intensity of 80 TECU occurred at 10.00 hrs UTC (Fig. 4). The 4th order ASHF model can capture both ionospheric quiet and disturbed EIA characteristics.

A. COMPARISON OF 4th ORDER ASHF MODEL WITH DUAL-FREQUENCY TEC MODELS

The performance of the 4th order ASHF model evaluated CODE-GIM model. To generate reference TEC maps by Assimilated Indian Regional Vertical Total Electron Content (AIRAVAT) model [17]. Fig. 6a shows observed latitudinal TEC profiles at 80°E longitudinal cross-section. The maximum TEC intensity of 80 TECU is observed at 11.00 hrs. UTC (16.30 LT) for the observed TEC map. Fig. 6b shows that Kp values are less than 3 indicate quiet ionospheric conditions. The northern EIA crest TEC structures are noticed at 9.00 hrs. UTC with maximum TEC intensity of 78 TECU (Fig. 6c). From Fig.6c- 6f show TEC results of CODE-GIM, and ASHF model. The 4th order ASHF is performed well compared to the CODE-GIM model. The TEC biases calculated by subtracting the observed and model TEC values. The 4th order ASHF model outperforms from CODE-GIM model. The maximum TEC biases value noted as 11TECU.

The proposed 4th order ASHF model performance compared to disturbed conditions (Fig.7). The early formation EIA TEC structures have occurred at 06.00 hrs. UTC (11.30LT) (Fig.7a). Fig.7b shows that Kp variations indicate disturbed ionospheric conditions. The disturbed EIA TEC structures (enhanced TEC intensities) are all well captured by AIRVAT (Observation) and 4th order ASHF models except the CODE GIM model. The biases of TEC results indicate that the ASHF model attains minimum bias TEC values as compared to CODE-GIM model. The proposed 4th order ASHF model is a strong contender of a near real-time ionospheric model for SBAS systems, especially for low and equatorial regions.

B. COMPARISON OF ASHF MODEL WITH SINGLE FREQUENCY IONOSPHERIC MODELS

The advantage of the 4th order ASHF model provides 25 model coefficients to estimate ionospheric delays over the Indian region. The ASHF model coefficients will be broadcasted to single-frequency GNSS users for ionospheric delay corrections. Furthermore, the ASHF model validated with Klobuchar model (Klob), CODEKlob model (Klobuchar-style coefficients provided by the Center for Orbit Determination in Europe (CODE), BeiDou System (BDS2) and NeQuick G models. Fig.8 and Fig. 9 shows single frequency ionospheric models (Klob, CODEKlob, BDS-2, and

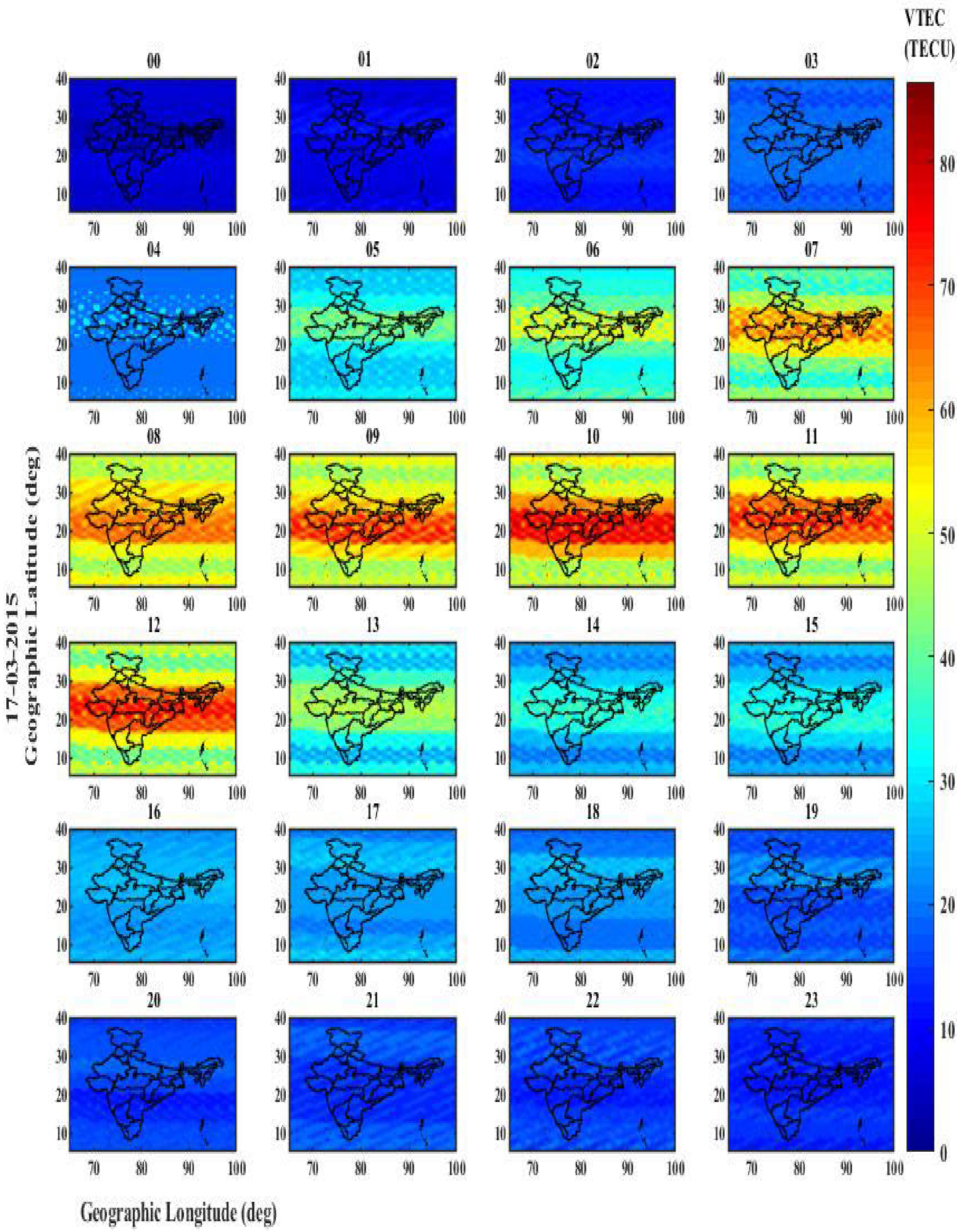

FIGURE 5. ASHF 4th-order TEC results for the geomagnetic disturbed day 17 March 2015.

NeQuick G) results for quiet and disturbed ionospheric conditions on 05 March 2015 and 17th march 2015 respectively. The BeiDou System (BDS2 model have predicted the ionospheric delays better than the Klobuchar model, NeQuick G and CODEKlob model. Nevertheless, the BDS-2 model has deviations by predicting larger EIA TEC intensities and smoother as compared to the proposed 4th order ASHF model. ASHF model is performing reasonably over the

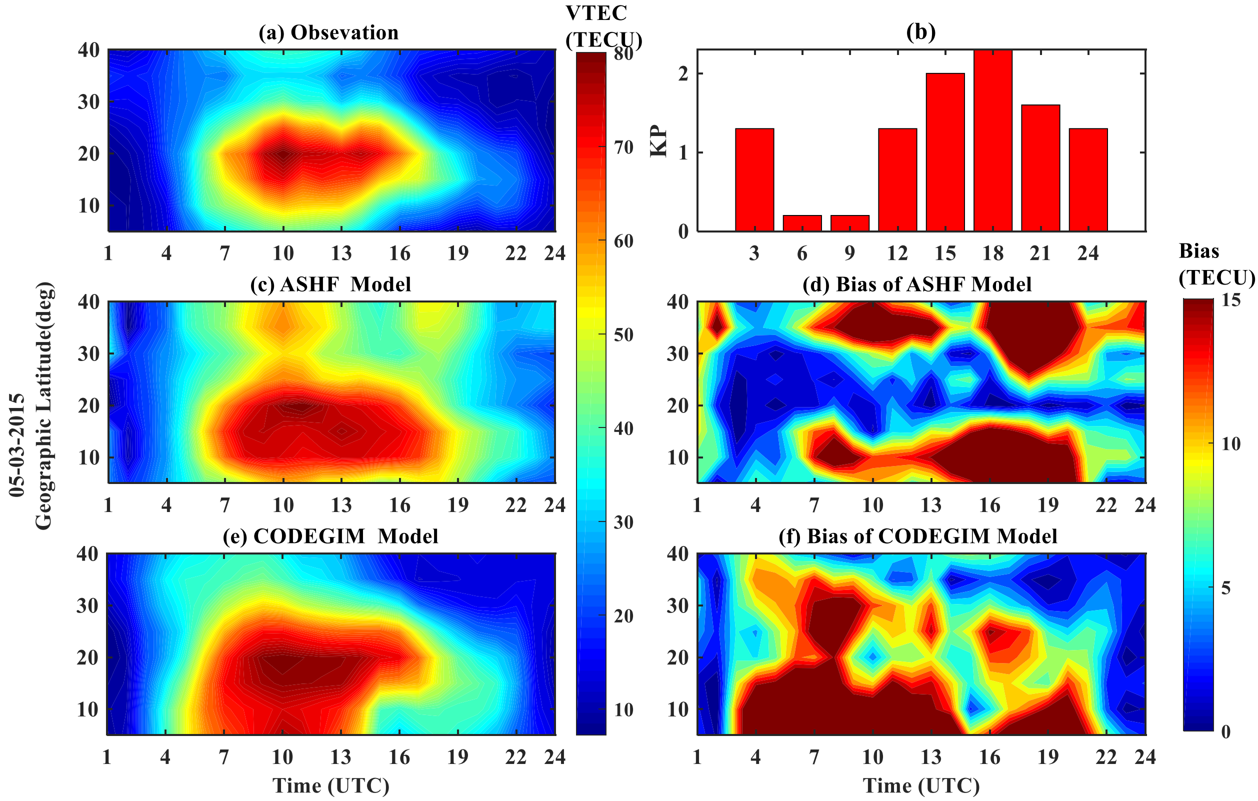

FIGURE 6. The ASHF Performance evaluation on dual frequency Ionospheric models during geomagnetic quiet day, 05 March 2015.

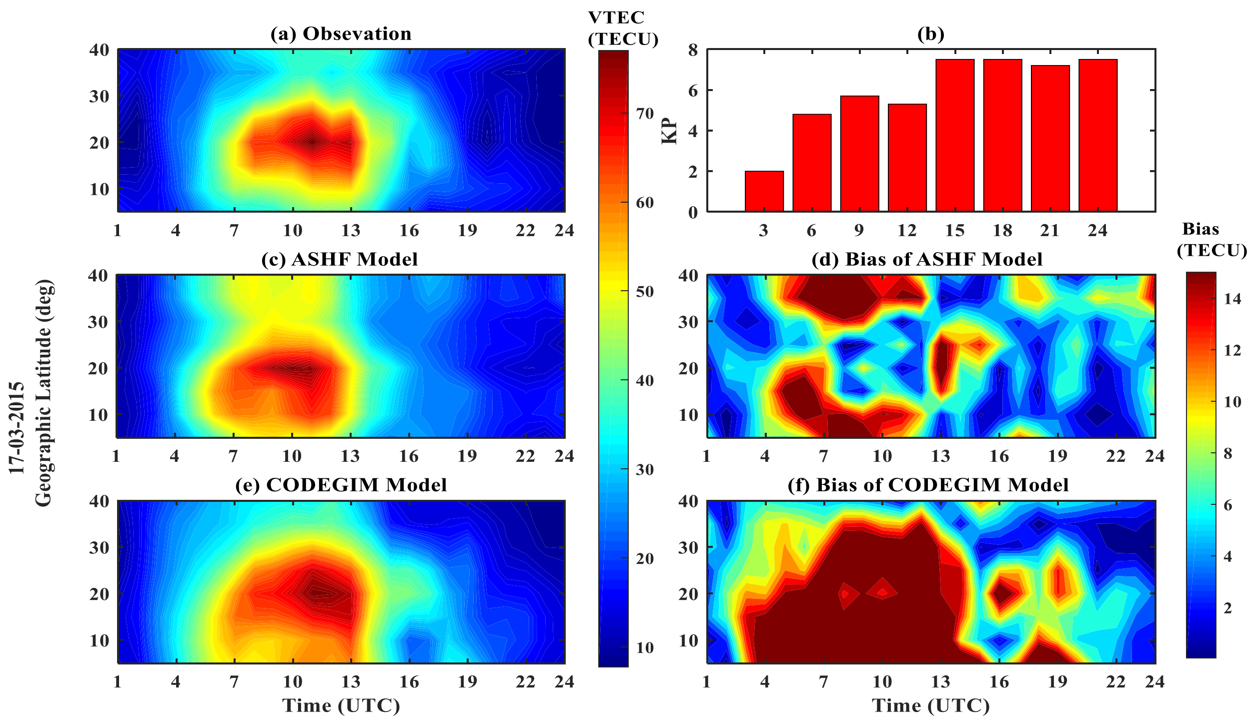

FIGURE 7. The ASHF Performance evaluation on dual frequency Ionospheric models during geomagnetic disturbed day, 17 March 201.

Indian region during geomagnetic quiet and disturbed days, 05 March 2015 and 17 March 2015. The ASHF model has outperformed BDS-2, CODEKlob, and Klobuchar models. The minimum TEC bias values of 7 TECU attained for the ASHF model (Fig. 8). The maximum bias values reached 15 TECU for the Klobuchar model. The bias value of all

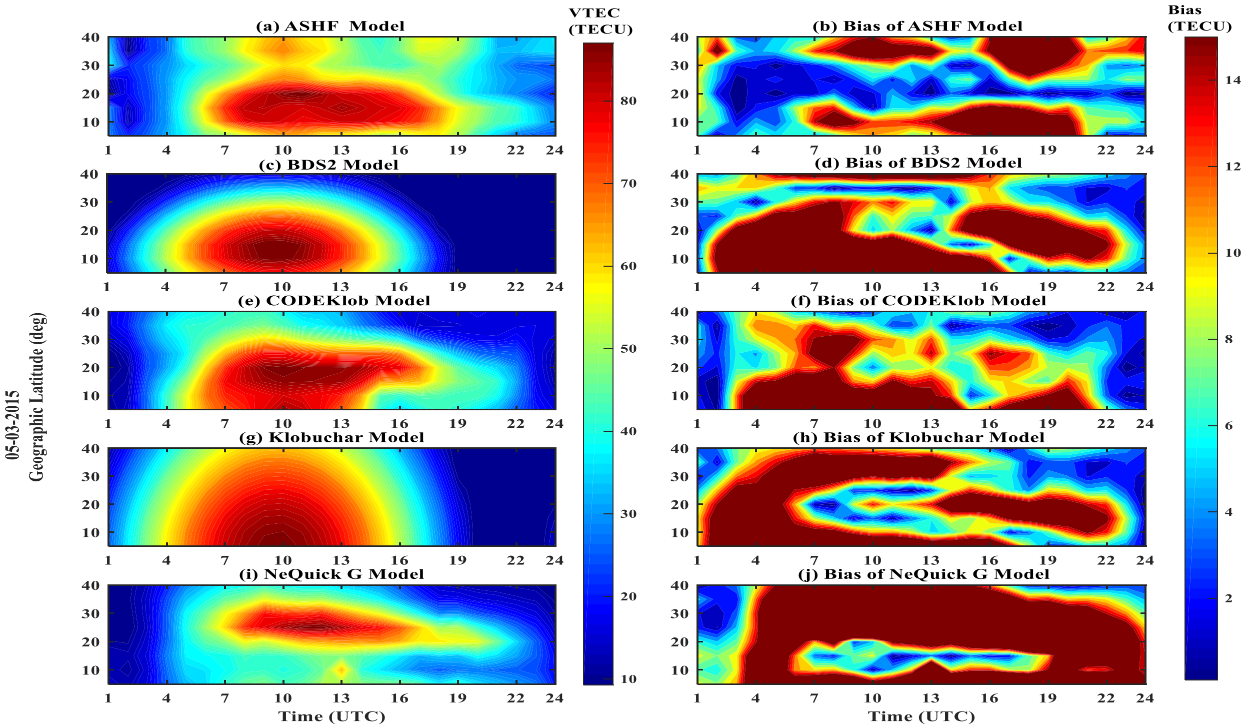

FIGURE 8. The ASHF Performance evaluation on single frequency Ionospheric models during geomagnetic quiet day, 05 March 2015.

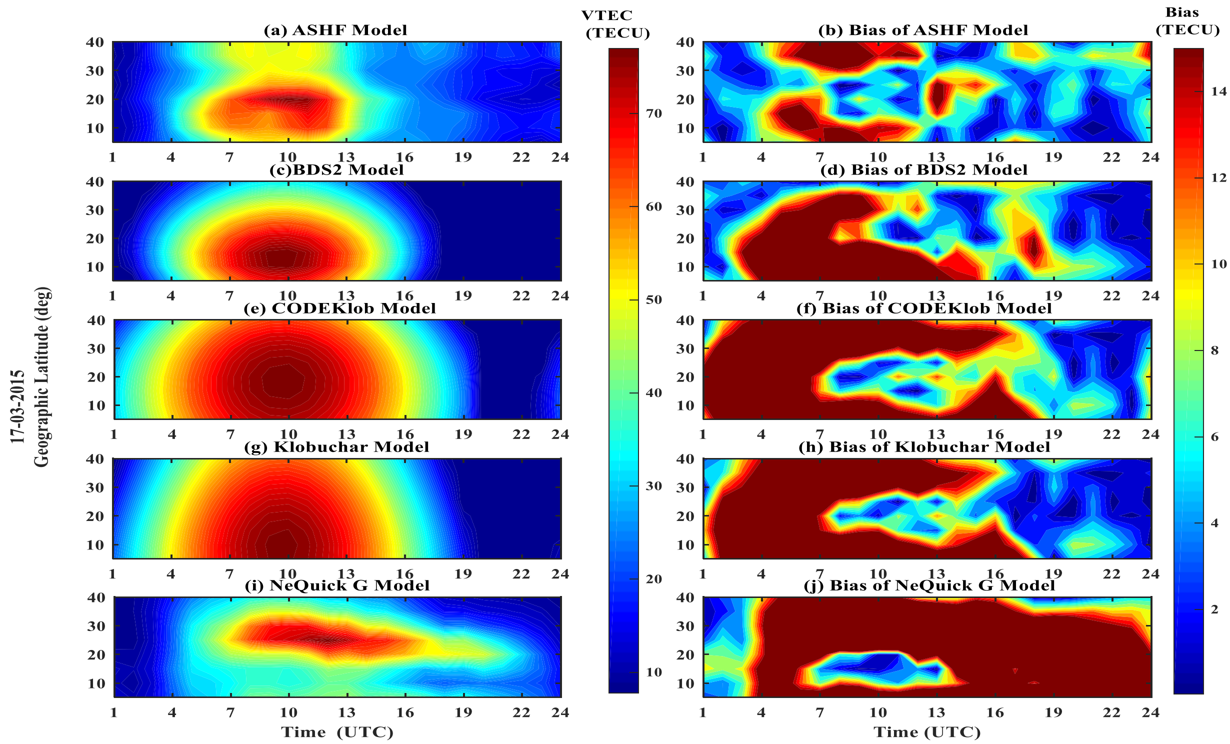

FIGURE 9. The ASHF Performance evaluation on single frequency Ionospheric models during geomagnetic disturbed day, 17 March.

single frequency ionospheric models is larger for disturbed days conditions than quiet day conditions (Fig. 8 and Fig. 9). It is observed that the 4th order ASHF model captures EIA TEC structures well when compared to BDS-2, CODEKlob, and Klobuchar and NeQuick G models. Thus, the proposed 4th order ASHF model can be useful as a regional single frequency ionospheric model for GNSS users over the Indian region.

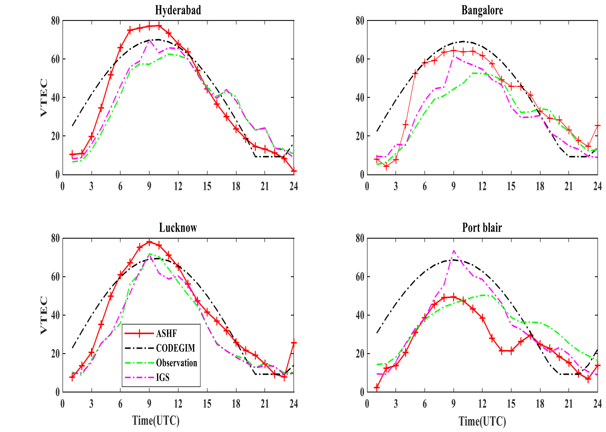

FIGURE 10. The performance analysis of dual-frequency models, proposed ASHF model (4th order), CODE GIM model, AIRAVAT model as observed data for VTEC diurnal variations observed over IGS stations, Hyderabad (HYDE) (17.6°N and 78.3° E), Bangalore (IISC) (13°N and 77.3°E), Lucknow (LCK4) (26.5°N and 80.5°E), Port Blair (PBRI) (11.3°N and 92.4°E) on 15 March 2015.

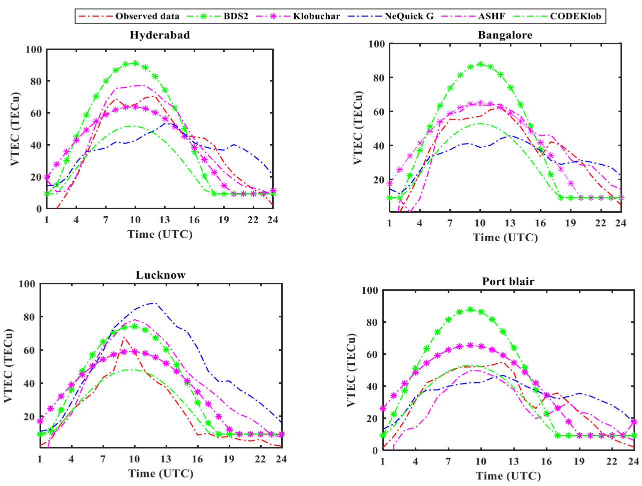

FIGURE 11. The performance analysis of single-frequency models, BDS2 model, Klobuchar model, NeQuick G model and CODEKlob model with observed data for VTEC diurnal variations observed over IGS stations, Hyderabad (HYDE) (17.6° N and 78.3° E), Bangalore (IISC) (13°N and 77.3° E), Lucknow (LCK4) (26.5°N and 80.5°E), Port Blair (PBRI) (11.3°N and 92.4° E) on 15 March 2015.

The 4th order ASHF model provides the lowest RMSE of 7.07 TECU and 6.60 TECU for quiet and disturbed ionospheric conditions of September 2015. The RMSE values lower for December solstice quiet day as compared to June solstice month (Table.2). Several authors [11], [32] have reported that the RMSE values of RIM models could be in the range of 3.8−16.2 TECu. Araujo-Pradere *et al.* (2007) [33] have reported that the accuracy of a RIM over the US is ∼2 TECU, which could be due to the low solar activity and mid latitude region. The maximum RMSE value for the proposed ASHF model is in the range of 6-13 TECu during the various seasons of the 24th high solar activity period, 2015 over Indian regions. The maximum RMSE is observed during March Equinox, June solstice and minimum RMSE is observed during December solstice and September Equinox periods. The vertical ionospheric delays during the disturbed days are quite low compared to quiet days due to the decrease in EIA during the disturbed days.

TABLE 2. Root Mean Square Error (RMSE) (TECu) values obtained from the proposed ASHF model with various ionospheric models during March & September Equinox and June & December Solstice days in 2015.

Equinox				
Model	05-03-2015	17-03-2015	27-09-2015	09-09-2015
ASHF-4th Order	**10.00**	**6.73**	**7.07**	**6.60**
CODEGIM	11.07	12.69	15.98	12.29
Klobuchar	9.73	11.53	13.51	9.58
BDS2	12.13	9.53	14.62	14.96
CODKlob	18.54	16.13	12.74	14.23
NeQuick G	18.48	16.78	19.69	19.55
Solstice				
Model	05-06-2015	23-06-2015	03-12-2015	20-12-2015
ASHF-4th Order	**13.85**	**9.53**	**7.17**	**6.43**
CODEGIM	10.47	10.24	8.30	13.42
Klobuchar	4.51	3.96	4.84	12.51
BDS2	7.53	3.66	6.05	11.19
CODKlob	22.66	18.98	16.65	13.04
NeQuick G	20.97	16.83	15.72	18.28

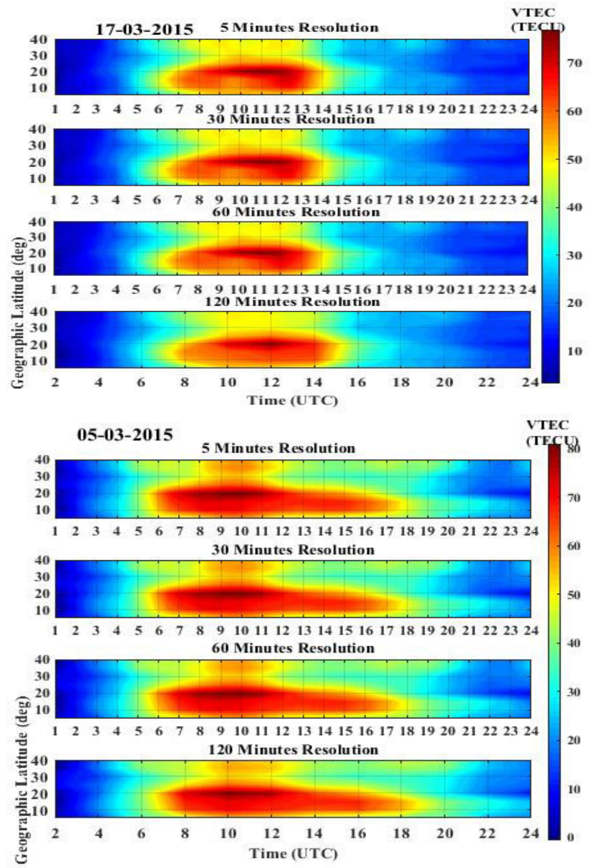

FIGURE 12. The ASHF Performance evaluation on time resolutions during geomagnetic quiet day, 05th March 2015, geomagnetic disturbed day, 17th March 2015.

TABLE 3. The comparison of ASHF model performance with ionospheric single-frequency models based on various positioning errors over Bangalore station during 15 March 2015.

	ASHF Model			
	Min	Max	Mean	Std
North error (m)	0.41	2.98	0.91	0.42
East error (m)	-1.98	0.64	0.06	0.67
Up error (m)	-2.21	2.88	-0.02	1.65
	Klobuchar Model			
North error (m)	-0.65	4.09	0.11	0.92
East error (m)	-2.44	0.80	-0.43	0.96
Up error (m)	-0.03	15.2	10.84	4.10
	NeQuick G Model			
North error (m)	0.36	3.02	0.78	0.45
East error (m)	-1.75	0.65	0.11	0.68
Up error (m)	-3.80	2.99	-1.51	2.35
	CODKlob Model			
North error (m)	0.28	2.92	0.75	0.46
East error (m)	-1.75	0.65	0.11	0.65
Up error (m)	-3.94	2.87	-1.37	2.31

Moreover, the performance of the proposed model, ASHF with 4th order has been compared with the dual frequency global ionospheric models (CODE GIM model, AIRAVAT as Observation model) and single frequency global ionospheric models (BDS2 model,Klobuchar model, NeQuick G model and CODEKlob model) as shown in Fig. 10 and 11 respectively. The performance of the 4th order ASHF model is tested with IGS GPS Stations (Bangalore, Port Blair, Lucknow, and Hyderabad) for 15 March 200015 data. IGS GPS TEC observations processed with GPS toolbox [27]. The maximum ionospheric time delay 80TECUnoted for Lucknow GPS station, whereas maximum ionospheric delay of 40TECU at Port Blair (near the equatorial station).

The 4th order ASHF model is following with all ionospheric models for estimating the diurnal ionospheric characteristics. The 4th order ASHF model is closely following the observed TEC values at Hyderabad, Bangalore, Port Blair, and Lucknow. Fig.12 illustrates 4th order ASHF model performance with different time update interval for broadcasting the coefficients in the form of a GNSS satellite navigation message. The ionospheric delay variations are becoming smoother as time update interval increases. The proposed twenty-five ASHF model coefficients can be uploaded to GNSS/NavIC satellites as part of the navigation message within a one-hour update interval.

Table 3 shows the comparison of position errors such as minimum, maximum, mean, and standard deviation values of the ASHF model with the different single frequency ionospheric models (Klobuchar model, NeQuick G model, and CODKlob models) over Bangalore IGS station. It is evident from the observations that the proposed 4th order ASHF model has lesser position errors (north, east, and up) compared with Klobuchar,NeQuick G and CODKlob models during the geomagnetic quit day (15-03-2015).

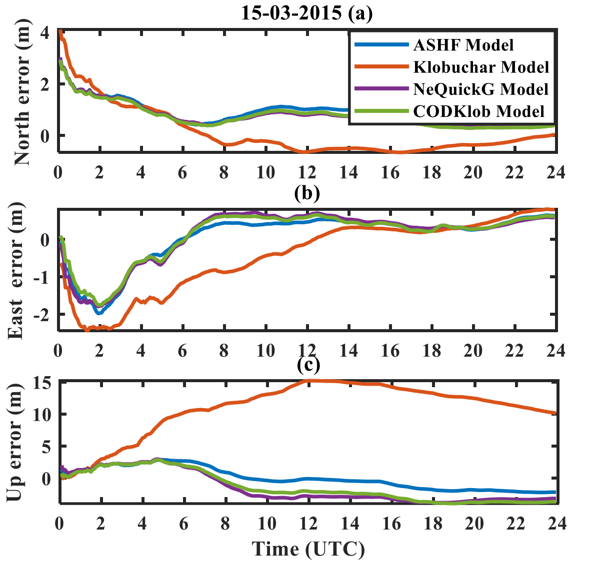

FIGURE 13. Comparison of the position errors of proposed regional ionospheric model, ASHF model with conventional ionospheric global models at Bangalore (IISC) (13°N and 77.3° E), ((a): north position errors; (b): east position errors; (c): up position errors).

The proposed ASHF model is validated with other conventional ionospheric models in terms of the Single Point Positioning (SPP) method using GLAB software [34]. Figure 13 illustrates the positioning errors of SPP solutions at Bangalore station. It is found that the proposed regional ionospheric model, ASHF model outperforms the global ionospheric models in terms of north, east, and up errors. Further, it is also noticed that the Nequick G model provides less positional errors as compared to CODEKlob and Klobuchar model as shown in Figure 13.

IV. CONCLUSION

The regional ionosphere TEC broad model based on the 4th order ASHF model is constructed for estimating the vertical ionospheric delay at different grid points using empirical data collected from 26 GPS TEC stations distributed throughout India. The performance of the proposed ASHF model validated in capturing the Equatorial Ionization Anomaly (EIA) patterns over the Indian region during the geomagnetic storm and quiet periods for the 2015data. The proposed 4th order ASHF model exhibits consistent better accuracy with dual-frequency models like CODE-GIM during all the geomagnetic conditions. The presented results show that adjusted spherical harmonics expansion model (with order = 4) estimates the ionospheric delays with high accuracy for SBAS application. The 4th order ASHF order driven by 25 coefficients alone and has the feasibility to act as regional GPS ionospheric broadcast model, i.e., broadcasting of these coefficients to NavIC/GNSS users. The RMSE values lower for December solstice month as compared to June solstice month.

The ASHF model coefficients can be valid up to one hour, respectively. It is suggested that a one-hour update interval of ASHF model coefficients for the GNSS/NavIC system is sufficient to represent dynamic and random ionospheric spatial-temporal variations in the Indian region.

REFERENCES

[1] K. Nishimoto, M. Ohashi, Y. Kubo, and S. Sugimoto, "Determination of the parameters of a Japanese-regional Klobuchar ionospheric model based on GR models and SCH analysis by GEONET data," in *Proc. ION Pacific PNT Meeting*, 2013, pp. 723–734.

[2] S. Schaer, "Mapping and predicting the Earth's ionosphere using the global positioning system," Ph.D. dissertation. Univ. Bern, Bern, Switzerland, 1999.

[3] A. K. Shukla, A. P. Shukla, V. S. Palsule, and S. Das, "Approach for near-real-time prediction of ionospheric delay using klobuchar-like coefficients for Indian region," *IET Radar, Sonar Navigat.*, vol. 7, no. 1, pp. 67–74, Jan. 2013.

[4] J. A. Klobuchar, "Ionospheric time-delay algorithm for single-frequency GPS users," *IEEE Trans. Aerosp. Electron. Syst.*, vol. AES-23, no. 3, pp. 325–331, May 1987, doi: 10.1109/TAES.1987.310829.

[5] W. A. Feess and S. G. Stephens, "Evaluation of GPS ionospheric time-delay model," *IEEE Trans. Aerosp. Electron. Syst.*, vols. AES–23, no. 3, pp. 332–338, May 1987.

[6] L. Han, H. Zhang, Y. Huang, M. Wang, W. Zhu, and J. Ping, "Improving Klobuchar type ionospheric delay model using 2D GPS TEC over China," in *Proc. 36th COSPAR Sci. Assem.*, 2006, p. 36.

[7] B. Nava, P. Coïsson, and S. M. Radicella, "A new version of the nequick ionosphere electron density model," *J. Atmos. Solar-Terrestrial Phys.*, vol. 70, no. 15, pp. 1856–1862, Dec. 2008.

[8] O. A. Oladipo and T. Schäler, "GNSS single frequency ionospheric range delay corrections: NeQuick data ingestion technique," *Adv. Space Res.*, vol. 50, no. 9, pp. 1204–1212, Nov. 2012.

[9] P. S. Jánior, D. B. M. Alves, and C. M. D. Silva, "Klobuchar and nequick G ionospheric models comparison for multi-GNSS single-frequency code point positioning in the Brazilian region," *Boletim de Ciáncias Geodésicas*, vol. 25, no. 3, p. 15, 2019.

[10] Y. Yuan, X. Huo, J. Ou, K. Zhang, Y. Chai, D. Wen, and R. Grenfell, "Refining the klobuchar ionospheric coefficients based on GPS observations," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 44, no. 4, pp. 1498–1510, Oct. 2008.

[11] N. Wang, Z. Li, X. Huo, M. Li, Y. Yuan, and C. Yuan, "Refinement of global ionospheric coefficients for GNSS applications: Methodology and results," *Adv. Space Res.*, vol. 63, no. 1, pp. 343–358, Jan. 2019.

[12] T. Rethika, S. Mishra, S. Nirmala, S. C. Rathnakara, and A. S. Ganeshan, "Single frequency ionospheric error correction using coefficients generated from regional ionospheric data for IRNSS," *Indian J. Radio Space Phys.*, vol. 42, pp. 125–130, Jun. 2013.

[13] R. Dach, E. Brockmann, S. Schaer, G. Beutler, M. Meindl, L. Prange, H. Bock, A. Jäggi, and L. Ostini, "GNSS processing at CODE: Status report," *J. Geodesy*, vol. 83, nos. 3–4, pp. 353–365, Mar. 2009.

[14] *Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment*, document RTCA/DO-229B, 1999.

[15] D. V. Ratnam, T. R. Vishnu, and P. B. S. Harsha, "Ionospheric gradients estimation and analysis of S-Band navigation signals for NAVIC system," *IEEE Access*, vol. 6, pp. 66954–66962, 2018.

[16] M. R. Kumar, M. Sridhar, D. V. Ratnam, P. B. S. Harsha, and S. N. Sri, "Estimation of ionospheric gradients and vertical total electron content using dual-frequency NAVIC measurements," *Astrophys. Space Sci.*, vol. 364, no. 3, p. 49, Mar. 2019.

[17] B. S. H. Pasumarthi and V. R. Devanaboyina, "Generation of assimilated indian regional vertical TEC maps," *GPS Solutions*, vol. 24, no. 1, p. 21, Jan. 2020.

[18] S. Sunda, R. Sridharan, B. M. Vyas, P. V. Khekale, K. S. Parikh, A. S. Ganeshan, C. R. Sudhir, S. V. Satish, and M. S. Bagiya, "Satellite-based augmentation systems: A novel and cost-effective tool for ionospheric and space weather studies," *Space Weather*, vol. 13, no. 1, pp. 6–15, Jan. 2015.

[19] N. Srinivasan, A. Ganeshan, and S. Mishra, "A new grid based ionosphere algorithm for GAGAN using data fusion technique (ISRO GIVE model-multi layer data fusion)," in *Proc. 39th COSPAR Sci. Assem.*, 2012, p. 1876.

[20] D. Venkata Ratnam and A. D. Sarma, "Modeling of low-latitude ionosphere using GPS data with SHF model," *IEEE Trans. Geosci. Remote Sens.*, vol. 50, no. 3, pp. 972–980, Mar. 2012.

[21] S. Karanam, D. Venkata Ratnam, and J. R. K. K. Dabbakuti, "Ionospheric time delay corrections based on the extended single layer model over low latitude region," *Geodesy Geodyn.*, vol. 10, no. 3, pp. 235–240, May 2019.

[22] J. R. K. K. Dabbakuti, D. V. Ratnam, and S. Sunda, "Modelling of ionospheric time delays based on adjusted spherical harmonic analysis," *Aviation*, vol. 20, no. 1, pp. 1–7, Apr. 2016.

[23] A. K. Shukla, S. Das, N. Nagori, M. R. Sivaraman, and K. Bandyopadhyay, "Two-shell ionospheric model for indian region: A novel approach," *IEEE Trans. Geosci. Remote Sens.*, vol. 47, no. 8, pp. 2407–2412, Aug. 2009.

[24] M. Fedrizzi, E. R. de Paula, I. J. Kantor, R. B. Langley, M. C. Santos, and A. Komjathy, "Mapping the low-latitude ionosphere with GPS," *GPS World*, vol. 13, pp. 41–47, 2002.

[25] J. Liu, R. Chen, Z. Wang, and H. Zhang, "Spherical cap harmonic model for mapping and predicting regional TEC," *GPS Solutions*, vol. 15, no. 2, pp. 109–119, Apr. 2011.

[26] J. Hopkins, "Computation of normalized associated Legendre functions using recursive relations," *J. Geophys. Res., USA*; vol. 78, no. 2, pp. 476–477, 1973.

[27] G. K. Seemala and C. E. Valladares, "Statistics of total electron content depletions observed over the south American continent for the year 2008," *Radio Sci.*, vol. 46, no. 5, pp. 1–8, Oct. 2011.

[28] Rao, PVS Rama, K. Niranjan, D. S. V. V. D. Prasad, S. Gopi Krishna, and G. Uma, "On the validity of the ionospheric pierce point (IPP) altitude of 350 km in the Indian equatorial and low-latitude sector," *Ann. Geophys.* vol. 24, pp. 2159–2168, Apr. 2006.

[29] P. V. S. R. Rao, S. G. Krishna, K. Niranjan, and V. D. Prasad, "Temporal and spatial variations in TEC using simultaneous measurements from the indian GPS network of receivers during the low solar activity period of 2004–2005," *Ann. Geophys.*, vol. 24, no. 12, pp. 3279–3292, Dec. 2006.

[30] C. B. A. D. Oliveira, T. M. S. Espejo, A. Moraes, E. Costa, J. Sousasantos, L. F. D. Lourenço, and M. A. Abdu, "Analysis of plasma bubble signatures in total electron content maps of the low-latitude ionosphere: A simplified methodology," *Surv. Geophys.*, vol. 41, no. 4, pp. 897–931, Jul. 2020.

[31] Guo, Jinyun, Wang Li, Xin Liu, Qiaoli Kong, Chunmei Zhao, and Bin Guo, "Temporal-spatial variation of global GPS-derived total electron content," *PLoS ONE*, vol. 10, no. 7, pp. 1999–2013, 2015.

[32] X. Zhao, S. Jin, C. Mekik, and J. Feng, "Evaluation of regional ionospheric grid model over China from dense GPS observations," *Geodesy Geodyn.*, vol. 7, no. 5, pp. 361–368, Sep. 2016.

[33] E. A. Araujo-Pradere, T. J. Fuller-Rowell, P. S. J. Spencer, and C. F. Minter, "Differential validation of the US-TEC model," *Radio Sci.*, vol. 42, no. 3, pp. n/a–n/a, Jun. 2007.

[34] D. Ibanez, A. Rovira-Garcia, J. Sanz, J. M. Juan, G. Gonzalez-Casado, D. Jimenez-Banos, C. Lopez-Echazarreta, and I. Lapin, "The GNSS laboratory tool suite (gLAB) updates: SBAS, DGNSS and global monitoring system," in *Proc. 9th ESA Workshop Satell. NavigationTechnologies Eur. Workshop GNSS Signals Signal Process. (NAVITEC)*, Dec. 2018, pp. 1–11.

KONDAVEETI SIVA KRISHNA received the M.Tech. degree in digital electronics and communication systems. He is currently a Senior Research Fellow (ISRO NGP-10 Project) and a Research Scholar with the Space Technology and Atmospheric Research Laboratory, Department of Electronics and Communication Engineering, Koneru Lakshmaiah Education Foundation, India. His research interests include ionospheric total electron content study, ionospheric total electron content modeling, study of ionospheric single frequency GPS receivers, developing algorithms of DCBs, and development ionospheric total electron content modeling using GPS aided GEO augmented navigation measurements.

DEVANABOYINA VENKATA RATNAM (Senior Member, IEEE) received the M.Tech. degree in radar and microwave engineering from the Department of Electronics and Communication Engineering, Andhra University, Visakhapatnam, India, in 2003, and the Ph.D. degree in electronics and communication engineering from Jawaharlal Nehru Technological University Hyderabad, Hyderabad, India, in 2011. From 2003 to 2011, he was a Research Assistant, a Junior Research Fellow, a Senior Research Fellow, and a Senior Research Assistant with the Research and Training Unit for Navigational Electronics, Osmania University, Hyderabad. In 2011, he joined the Department of Electronics and Communications Engineering, as an Associate Professor (Faculty Member). He is currently a Professor and the Head of the Centre for Atmospheric Sciences, KL University, Guntur, India. He has published more than 30 journal articles. His research interests include navigational electronics, global navigational satellite systems (GNSS), space science, and radio-wave propagation. He was a recipient of the Young Scientist Award from the Department of Science and Technology (DST), India, from 2012 to 2015, the Research Award of the University Grants Commission (UGC), India, from 2015 to 2017, and the Early Career Research Award from the Science and Engineering Research Board (SERB), India, from 2017 to 2020.

MIRIYALA SRIDHAR (Senior Member, IEEE) received the Ph.D. degree from JNTU Kakinada, Kakinada, India, in 2017, and the M.Tech. degree from Jawaharlal Nehru Technological University, Anantapur, India, in 2009. He has 17 years of teaching experience. He is currently a Professor with Koneru Lakshmaiah (KL) University, Guntur, India. He is also one of the members of IRNSS/NAVIC Project in collaboration with KL University and the Space Applications Centre (SAC), Ahmedabad, India. He has published research papers in 15 international journals and five international/national conferences. His research interests include developing ionospheric scintillation mitigation algorithms and satellite communications. He is a Senior Member of the Institution of Electronics and Telecommunications Engineers (IETE).

P. BABU SREE HARSHA (Graduate Student Member, IEEE) received the M.Tech. degree in communications and radar systems. He worked on carrier tracking algorithms for GNSS receivers in mitigation of ionospheric scintillations using Kalman filter techniques. He is currently a Junior Research Fellow with the Space Technology and Atmospheric Research Laboratory, Department of Electronics and Communication Engineering, Koneru Lakshmaiah Education Foundation (KL University), India. His research interest includes developing data assimilation algorithms for ionospheric variables.

GAMPALA SIVAVARAPRASAD (Member, IEEE) received the M.Tech. degree from KL University, Guntur, India, in 2015, and the Ph.D. degree from the Department of ECE, KL University, in 2018. In 2017, he joined the Department of ECE, KL University, as an Assistant Professor (Faculty Member), where he is currently an Assistant Professor with the Department of Electronics and Communication Engineering. His research interests include satellite and wireless communication systems, space weather studies of upper atmosphere, study of ionospheric irregularities using GPS-based total electron content and scintillations measurements, and development of web-based ionospheric system-based on deep learning techniques for ionospheric total electron content forecasting and mitigation of scintillation effects using GNSS/NavIC observations. He was a recipient of the Early Career Research Award from the Science and Engineering Research Board (SERB), India.