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A New Ionospheric Model for Single Frequency GNSS User Applications Using Klobuchar Model Driven by Auto Regressive Moving Average (SAKARMA) Method Over Indian Region

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ABSTRACT The single-frequency users of Global Navigation Satellite System (GNSS) require an effective mathematical model that mitigate the dominant errors due to ionospheric delays. Klobuchar model approximately reduces ionospheric effect up to 50% through its coefficients in the navigation message, which is not sufficient for the GNSS single frequency users at critical applications. Hence, a new model, for Single Frequency GNSS User Applications using Klobuchar model driven by Auto Regressive Moving Average Method (SAKARMA) is proposed to forecast and enhance the precision of ionospheric delay estimations for GNSS users. The hourly VTEC maps are obtained from the Assimilated Indian Regional Vertical Total Electron Content (AIRAVAT) by the process of data assimilation using the Kalman filter exclusively for the Indian region (longitude: 65°E to 100°E; latitude: 5°N to 40°N) using 26 GPS TEC stations over Indian region. The accuracy of the SAKARMA model is investigated using the AIRAVAT maps for various Indian geographic regions during both geomagnetic quiet and disturbed conditions of September month in 2016 year. Furthermore, in order to test SAKARMA model, a dual-frequency Navigation with Indian Constellation (NavIC) receiver located at the KL Education Foundation, Guntur, India (geographic: 16.37°N, 80.37°E; geomagnetic: 7.44°N, 153.75°E) is used to collect the observations during 2 - 12 September 2017. Furthermore, SAKARMA model is also validated with Klobuchar model, Klobuchar-style coefficients provided by the Center for Orbit Determination in Europe (CODE) (CODKlob) Model, BeiDou System (BDS2) Model and NeQuick 2 Model over a low latitude NavIC station in forecasting the ionospheric delays. The experimental results of SAKARMA for NavIC have revealed that the MAPE for proposed SAKARMA model is 9-17% (accuracy: 83-91%), while 34-53% (accuracy: 47-66%) for the Klobuchar model. Thus, the results illustrate that the proposed SAKARMA model is capable of predicting the ionospheric delays for single frequency GNSS/NavIC users.

INDEX TERMS GNSS, NavIC, ionospheric delay, Klobuchar model, auto regressive moving average (ARMA) model, SAKARMA model.

I. INTRODUCTION

The reliability of positioning and navigation applications of Global Navigation Satellite System (GNSS) is vulnerable to

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ionospheric effects. The ionospheric time delay contributes to one of the most significant errors in the measurements of satellite based radio navigation systems [1]. The level of positioning errors for regional (or) global satellite system due to ionospheric delay depends on the "Total Electron Content" (TEC) over the region of interest (local time, geographic location of the receiver) and radio frequency of the signal $I = 40.3/cf^2 * TEC$ [2]. The ionospheric delay in GNSS measurements can be corrected using the dual-frequency observations exploiting the dispersive nature of the ionosphere [3]. Nonetheless, in real time, the ionospheric errors continue to remain a threat to the positioning and navigation applications of single frequency GNSS receiver users as the ionospheric errors can range up to 100 m.

Klobuchar [1] has developed a global ionospheric delay model known as ionospheric broadcasting model (IBM) for the benefit of single frequency Global Positioning System (GPS) users. It provides ionospheric corrections in real time applications with only 8 coefficients in the GPS navigation message. However, the Klobuchar model does not consider the local ionospheric weather conditions and cannot provide temporal variations in ionospheric delay due to fixed values in its algorithm to obtain peak at 14-h local time (LT) and 5 ns or 9.24 TECU of delay during night-time hours [4]. Moreover, the Klobuchar model accuracy is limited in estimating the regional ionospheric delays especially over low latitude region, which exhibits dynamic variations in electron content anomalies due to ionisation crests [5], [6]. Liu *et al.* have reported that anomalies in Klobuchar coefficients influence ionospheric corrections for the single frequency GNSS users which are predefined in the GPS system for a particular solar cycle condition [7]. Thereby, the efficiency of Klobuchar model to estimate the vertical delay is about 50-60% since the transmitted coefficients are not updated daily and remain the same for about 10 days [1], [8], [9]. Consequently, the estimation and removal of ionospheric delay errors in the real-time applications of the single frequency users continued to remain a potential challenge to be addressed. Various researchers, Han *et al.*, Yuan *et al.*, Filjar *et al.*, Lee *et al.*, Shukla *et al.*, Wang *et al.*, etc., [4], [9]–[13] have worked on different aspects by adding several parameters for improving the performance of Klobuchar model. The effectiveness of these Klobuchar-like models developed by the addition of several new parameters could yield an accuracy not exceeding 70% during geomagnetic disturbed conditions; which definitely is not sufficient for safety critical single frequency GNSS user applications that demand high accuracy.

Indian Space Research Organisation (ISRO) has developed India's own GPS known as Indian Regional Navigation Satellite System (IRNSS) named as Navigation with Indian Constellation (NavIC) which provides user's 3- dimensional position, space and time over and around 1500 km area of Indian region with more positioning accuracy than other GNSS systems. Rethika *et al.* have proposed the methodology for correction of Klobuchar coefficients for NavIC single frequency users [14]. The evaluation of the Klobuchar model in Taiwan worked by Li *et al.* has illustrated that the differences between the Klobuchar model and the measured dual-frequency ionospheric delays vary with solar activity and latitudes also [15]. Chen *et al.* have proposed a Sophisticated Klobuchar Model (SKM) based on Holt-Winters exponential smoothing model over China region and tested for one day using six days of training data sets [16]. This method has focused to fill the missing data for dual-frequency receiver and forecasting ionospheric delays. Xing Li *et al.* have observed the degradation in the ionospheric correction rates of Beidou/GPS system models during the geomagnetic storm condition of high solar activity period, 2015 [17].

In this paper, a new model, SAKARMA method is proposed and evaluated over Indian region using AIRAVAT VTEC maps and the dual-frequency NavIC receiver observations. The accuracy of the SAKARMA model is compared with Klobuchar model, Klobuchar-style coefficients provided by the Center for Orbit Determination in Europe (CODE) (CODKlob) Model, BeiDou System (BDS2) Model and NeQuick 2 Model in forecasting the ionospheric delays during both geomagnetic quiet/disturbed days in September 2016. Moreover, the SAKARMA model is also tested in estimating the occurrence of Equatorial Ionization Anomaly (EIA) features for all the Indian latitudes over 80 degrees (80°E) of longitude during both geomagnetic conditions. The details of proposed SAKARMA algorithm and validation process is described in Section 2 followed by experimental results and discussion in Section 3 and the conclusion and future work are elucidated in Section 4.

II. DATA AND PROPOSED IONOSPHERIC SAKARMA MODEL

The VTEC maps generated from Assimilated Indian Regional Vertical TEC (AIRAVAT) covers the geographic latitudes from 5° to 40° and longitudes from 65° to 100° with spatial grid of 2.5° latitude by 5° longitude (120 grid points) over the Indian region with a temporal resolution of one hour (1 h) [18]. The VTEC data from AIRAVAT maps during 1-30 September 2016 is considered to validate the SAKARMA model. The ionospheric delays estimated using measurements of NavIC system are also considered for a period of 11 days (2-12 September 2017) in the present work. NAVIC system developed by ISRO consists of 7 satellites in its constellation with 3 Geo-Stationary Orbit (GEO) and 4 Geo Synchronous Transfer Orbit (GSO)). The NavIC technology provides position, navigation and timing services along with services to monitor the ionospheric space weather [19], [20]. The Geostationary Earth Orbit (GEO) satellites are highly potential for ionospheric research especially in near equatorial region due to their negligible motion in Ionospheric Pierce Point (IPP) [21], [22]. As the Indian geographical region comes under the low latitudes and prone to EIA effects on the satellite communication and navigation links, NavIC GEO satellites would facilitate in monitoring the dynamic changes in low-latitude ionosphere [23].

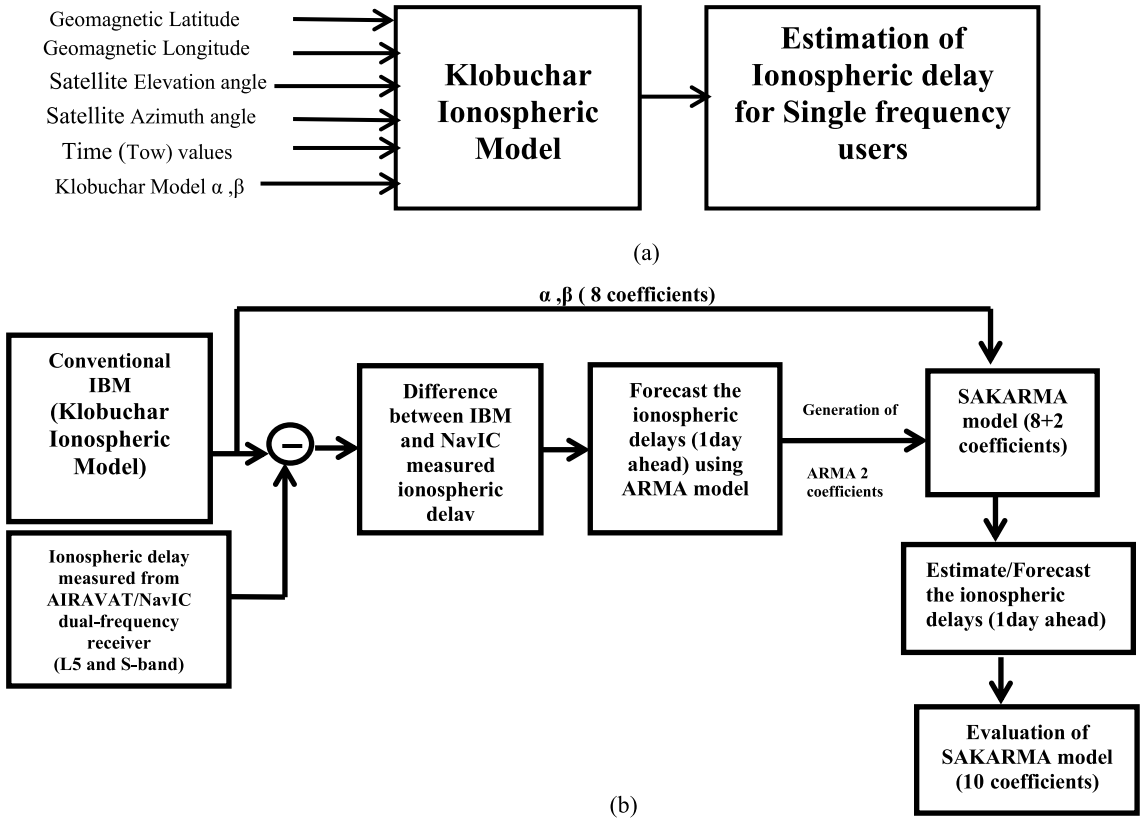

FIGURE 1. (a) The conventional Klobuchar model as Ionospheric Broadcasting Model (IBM), (b) Proposed SAKARMA ionospheric model for ionospheric error corrections to single frequency GNSS/NavIC users.

The estimation of Differential Code Biases (DCBs) are crucial due to their high temporal variability and effect on the accurate determination of absolute ionospheric TEC [24]. The NavIC DCBs are estimated on daily basis with the support of International Reference Ionosphere Extended to Plasmasphere (IRI-Plas) model, and GPS receiver available at Koneru Lakshmaiah Education Foundation, Guntur, India. The NavIC ionospheric delay values are estimated after removing the DCBs [25].

The proposed improved Klobuchar model based on ARMA model (SAKARMA model) provides an additional two coefficients for the derived eight coefficients of Klobuchar Ionospheric Broadcasting Model (IBM) algorithm from GPS/NavIC navigation message. The proposed algorithm is arrayed in flow chart labelled Fig.1(b). The proposed SAKARMA model algorithm is explicated step by step as follows:

STEP-1: The mathematical expression for the proposed algorithm is given as,

$$[I_{SAKARMA}]_{hr\times d} = [K_{iono}]_{hr\times d} + [FR_{iono}]_{hr\times d} \tag{1}$$

$I_{SAKARMA}$ refers to the ionospheric delay estimated/forecasted one day ahead (for hr refers to 24 hours and days, d = 1 day) from the proposed SAKARMA Method, K_{iono} refers to the ionospheric delays estimated from the Klobuchar model during testing day, d,

FR_{iono} refers to the ARMA forecasted residual between Klobuchar model and observed AIRAVAT/NavIC delay values during testing day, d.

STEP-2: The calculation of ionospheric delay for Klobuchar model is based upon the following equations from [1]. The $[K_{iono}]_{hr\times d}$ matrix denotes the Klobuchar model estimated ionospheric delay values given by [1],

$$\therefore K_{iono} = \begin{cases} F^*[5^*10^{-9} + amp(1 - \frac{X^2}{2} + \frac{X^4}{24}), & |X| < 1.57 \\ F^*(5^*10^{-9}), & |X| \geq 1.57 \end{cases} \tag{2}$$

where, $amp = \sum_{n=0}^{3} \alpha_n \phi_m^n$, $amp \geq 0$,

$$X = \frac{2\pi(t - 50400)}{T}\,(rad)\,,$$

$$T = \sum_{n=0}^{3} \beta_n \phi_m^n, \quad T > 72,000,$$

If $T \leq 72,000$,
The mapping function,

$$f = 1.0 + 16.0[0.53 - elv]^3 \tag{3}$$

where, α_n and β_n are the coefficients which are obtained from GPS navigation message of the GPS/NavIC receiver, φ_m is the geomagnetic latitude of the Ionospheric Pierce Point (IPP)

of the satellite receiver ray path at the height of 350 km, T denotes the ionospheric period delay and elv is the elevation angle in semicircle, 'amp' is the amplitude of the ionospheric delay.

STEP-3: The required parameters to build the ionospheric delays from Klobuchar model are obtained from the NavIC receiver RINEX files. The time T (time of week, TOW) in seconds and in addition the azimuth angle and Elevation angle are taken from the GPS/NavIC receiver.

STEP-4: The raw pseudorange and carrier phase measurements for all the NavIC satellites in view are obtained from RINEX ver 3.03 observation file of NavIC receiver. The slant ionospheric delay values are measured from raw pseudorange and carrier phase measurements of dual frequency (L5 and S band) NavIC receiver. Later the vertical delays are calculated as per below equation.

$$V_{iono} = S_{iono} \times MF(El) \tag{4}$$

where,

$$MF(El) = \left[1 - \left(\frac{\cos(El)}{1 + \frac{h_{iono}}{R_e}}\right)^2\right]^{-\frac{1}{2}}.$$

Here, V_{iono} are the vertical ionospheric delay values, S_{iono} are the slant ionospheric delay values, El is the elevation angle of all NavIC satellites, Re is the Earth's radius in kilometers, h_{iono} is the height of the maximum electron density at the F2 peak, 350 km [26].

In order to avoid the noise from the pseudo-range measurements and integer ambiguity from carrier phase measurements differential correction (L5 and S- band) based Weighted Least Squares (WLS) model is utilized [27]. The modelled VTEC from WLS algorithm is chosen as the input for the implementation of the proposed SAKARMA model [27].

STEP-5: The difference between measured ionospheric delay values derived from AIRAVAT/NAVIC and Klobuchar model is given in the below equation,

$$[R_{iono}]_{1\times M} = [V_{iono}]_{1\times M} - [K_{iono}]_{1\times M} \tag{5}$$

Later, the $[R_{iono}]_{1\times M}$ time series will be rearranged as shown in the following mathematical expression,

$$[R_{iono}]_{hr\times d} = \begin{array}{c} \text{Days} \rightarrow \\ \downarrow \textit{hours} \\ 1 \\ 2 \\ 3 \\ . \\ . \\ 24 \end{array} \begin{array}{c} 1 \quad 2 \quad 3 \quad \ldots \quad \text{N days} \\ \begin{bmatrix} R_{11} & R_{12} & R_{13} & . & . & R_{1N} \\ R_{21} & R_{22} & R_{23} & . & . & R_{2N} \\ R_{31} & R_{32} & R_{33} & . & . & R_{3N} \\ . & . & . & & & . \\ . & . & . & & & . \\ R_{h1} & R_{h2} & R_{h3} & . & . & R_{hN} \end{bmatrix}_{hr\times d} \end{array} \tag{6}$$

$M = hr.d$ refers to the number of samples during number of hours and days of investigation period.

N refers to days, $R_{hr\times d}$ refers to the delay residuals of Klobuchar model with respect to the measured AIRAVAT/NavIC ionospheric delay values. Here, d refers to the number of selected days as the training period.

STEP-6: The required coefficients and residual ionospheric delay FR_{iono} is estimated using an ARMA (p, q) (Auto Regressive Moving Average Model with the orders p and q) model applying on R_{iono} residual time series with the followed mathematical expression [28],

$$\begin{bmatrix} FR_{iono1} \\ FR_{iono2} \\ FR_{iono3} \\ . \\ . \\ FR_{iono_N} \end{bmatrix} = \begin{bmatrix} (\phi_1 R_{t-1} + \ldots\ldots + \phi_p R_{t-p})_1 \\ (\phi_1 R_{t-1} + \ldots\ldots + \phi_p R_{t-p})_2 \\ (\phi_1 R_{t-1} + \ldots\ldots + \phi_p R_{t-p})_3 \\ . \\ . \\ (\phi_1 R_{t-1} + \ldots\ldots + \phi_p R_{t-p})_N \end{bmatrix} + \begin{bmatrix} (\theta_1 \varepsilon_{t-1} + \ldots . \theta_q \varepsilon_{t-q})_1 \\ (\theta_1 \varepsilon_{t-1} + \ldots . \theta_q \varepsilon_{t-q})_2 \\ (\theta_1 \varepsilon_{t-1} + \ldots . \theta_q \varepsilon_{t-q})_3 \\ . \\ . \\ (\theta_1 \varepsilon_{t-1} + \ldots . \theta_q \varepsilon_{t-q})_N \end{bmatrix} \tag{7}$$

where, ϕ, θ refers to the coefficients of AR and MA processes respectively, R_t refers to Ionospheric delay residual values, R_{iono}, at time t (for t = 1, 2, 3…t hours), (p, q) denotes the orders of AR and MA respectively, $\varepsilon(t)$ refers to the white noise and N refers to N number of days.

The process $\{FR_{iono}\}$ is said to be an ARMA (p, q) process with mean μ if $\{FR_{iono} - \mu\}$ is an ARMA (p, q) process. In this proposed method, the ARMA (1,1) is used. Thus, SAKARMA model provides 2 coefficients derived from the residual during its training period in addition to 8 Klobuchar model coefficients to forecast the ionospheric delay values during testing period.

STEP-7: SAKARMA model derives an additional 2 coefficients (to be included for Klobuchar model) based on the time series of difference between measured AIRAVAT/NavIC ionospheric delay and Klobuchar model during the training period. The SAKARMA model provides one day ahead forecast of additional coefficients and the ionospheric delay values (testing period).

Finally, the proposed SAKARMA method is evaluated based on Mean Absolute Error (MAE), Mean Absolute Percentage Error (MAPE) in terms of %, Mean Square Error (MSE), Root Mean Square Error (RMSE) and Goodness of fit (R^2) and relative error.

III. RESULTS AND DISCUSSION

The proposed coefficients-based time series model, i.e. SAKARMA model is evaluated for both spatio temporal datasets using the AIRAVAT VTEC maps over Indian region and NAVIC observations at single low latitude station. Additionally, SAKARMA model is also validated for both the geomagnetic quiet and disturbed days during 1-30 September of 2016 using the AIRAVAT maps and 2-12 September 2017 years using the NAVIC observations respectively. The VTEC maps from AIRAVAT are considered as it is data assimilation technique based on

Kalman filer using the regional ionospheric space weather data from space and ground-based satellite observations over India [18]. Thus, AIRAVAT VTEC maps facilitated to evaluate the performance of the SAKARMA model on the spatial basis over Indian region. In the present work, the performance of the proposed model is also compared with other broadcasted models used for single frequency users. Hence, modified Klobuchar model style global ionospheric broadcast models such as CODKlob model [29] and BDS2 model [30] are considered in the present work to validate the proposed model. The alpha and beta coefficients of Klobuchar like model BDS-2 are obtained from (ftp://cddis.nasa.gov/gnss/data/daily/) and the alpha and beta coefficients of CODKlob model are obtained from (ftp://ftp.gipp.org.cn/product/brdion/). The VTEC values of NeQuick 2 model are obtained from (https://t-ict4d.ictp.it/nequick2/nequick-2-web-model) during the period of investigation.

The geomagnetic Dst index is used to identify the quiet and disturbed ionospheric TEC periods. The disturbance in the horizontal component of Earth's magnetic field is represented by Dst index. It is obtained from the average value of magnetic field horizontal components measured at four near-equatorial geomagnetic observatories [31]. The Dst index values can be obtained from (http://wdc.kugi.kyoto-qu.ac.jp/dst_provisional/201609/index.html). Firstly, the proposed methodology in the Section 2 is implemented for the AIRAVAT VTEC maps to assess the SAKARMA model accuracy during geomagnetic quiet day, 16 September 2016 (DST index indicates the value is in the range of 7 nT to −4 nT) and then the geomagnetic disturbed day, 29 September 2016 (DST index indicates the value is in the range of −24 nT to −66 nT) respectively. The geomagnetic quiet day, ionospheric TEC maps are forecasted using SAKARMA model with hourly AIRAVAT maps as an input from 1 September to 15 September 2016. The SAKARMA model has run the input AIRAVAT maps for all the latitudes and longitudes over Indian region during this training period. Fig. 2 shows the AIRAVAT VTEC maps, Klobuchar model VTEC maps, CODKlob model VTEC maps and SAKARMA model VTEC maps for different Universal Time Coordinated (UTC) hours (07:00UTC, 10:00UTC, 12:00 UTC and 15:00 UTC) over the entire Indian region.

As noticed from the Fig. 2, the X-axis refers to the longitudes that range from 65° E to 100° E, Y-axis refers to the latitudes that range from 5° N to 40° N and colorbar refers to the VTEC (TECU). It can be apparently observed from Fig. 2, that the SAKARMA model is able to replicate the AIRAVAT VTEC patterns during all the different UTC hours compared to the Klobuchar model and CODKlob model due to its additional 2 coefficients for the Klobuchar model. The spatiotemporal VTEC patterns (TECU) of AIRAVAT VTEC maps are well captured by SAKARMA model than Klobuchar model and CODKlob model as seen from Fig. 2. Moreover, the SAKARMA model has clearly forecasted the occurrence of the EIA patterns as seen from AIRAVAT maps including the initiation (07:00 UTC), arriving towards (10:00 UTC) Indian region, occupancy (12:00 UTC) and exit (15:00 UTC) of EIA over Indian region as observed from Fig.2. Though the CODKlob model has provided better VTEC patterns than Klobuchar model in Fig.2, it showed more deviations over certain latitudes and longitudes indicating that it is overestimation with respect to AIRAVAT VTEC values. The SAKARMA model could outperform Klobuchar model because, it is more adaptive to capture the short-term variations of spatial ionospheric TEC using AR and MA coefficients obtained from the residual of Klobuchar model with AIRAVAT VTEC values.

Fig. 3 shows the absolute actual differences of Klobuchar model, CODKlob model and proposed SAKARAMA model with the AIRAVAT VTEC maps during 16 September 2016. It is observed that SAKARMA model yields less forecasting errors compared to Klobuchar model and CODKlob model for all the different UTC hours over the Indian region during the geomagnetic quiet day (16 September 2016). The bias of SAKARAMA model with the AIRAVAT VTEC values is 1-3 TECU at all the different UTC hours considered. Howbeit, the biases of Klobuchar model with AIRAVAT VTEC values are up to 7 TECU at 07:00 UTC hours, 16 TECU at 10:00 UTC hours, 18 TECU at 12:00 UTC and 15:00 UTC hours respectively at 15-20° N. The bias values of the CODKlob model read 16 TECU at 25-30°N and 90-95°E during 7 UTC hours and 10-16 TECU at 25-35°N and 78-80°E during 10 UTC hours. However, it should also be noted that the bias values of the CODKlob model for the rest of the Indian region read 4-8 TECU during 10 UTC hours.

Also, CODKlob model has performed better than Klobuchar model by 8-10 TECU units during 12 UTC hours and 15 UTC hours. The availability of the regional ionospheric observations over the Indian region aided SAKARMA model to perform consistent and par excellence when compared to Klobuchar and CODKlob models. The validation of the SAKARMA model using Mean Absolute Error (MAE), Mean Square Error (MSE) and Mean Absolute Percentage Error (MAPE) substantiates that SAKARMA model produces an accuracy of 95% with lower forecasting error values (MAE = 0.19-2.3 TECU, MSE = 0.016-13 TECU) and higher forecasting accuracy values (MAPE = 5.0%) during the geomagnetic quiet day, 16 September 2016 over Indian region. It can also be observed from Table. 1, that the Klobuchar model have high forecast error values (MAE = 8.9 TECU, MSE = 4.6-121 TECU) and lower forecasting accuracy values, MAPE = 25.8% yielding an accuracy of 74.2%. However, CODKlob model has poor MAE and MSE values, while the MAPE is 8% more than Klobuchar model. Table. 1 thereby reflects the facts endorsing the conclusions drawn from Fig 2 and Fig 3 regarding the SAKARMA, Klobuchar and CODKlob models.

The SAKARMA model is trained for 1 September to 28 September 2016 to forecast the VTEC values over Indian region during geomagnetic disturbed day 29 September 2016 (test period). Fig. 4 shows the AIRAVAT VTEC maps and

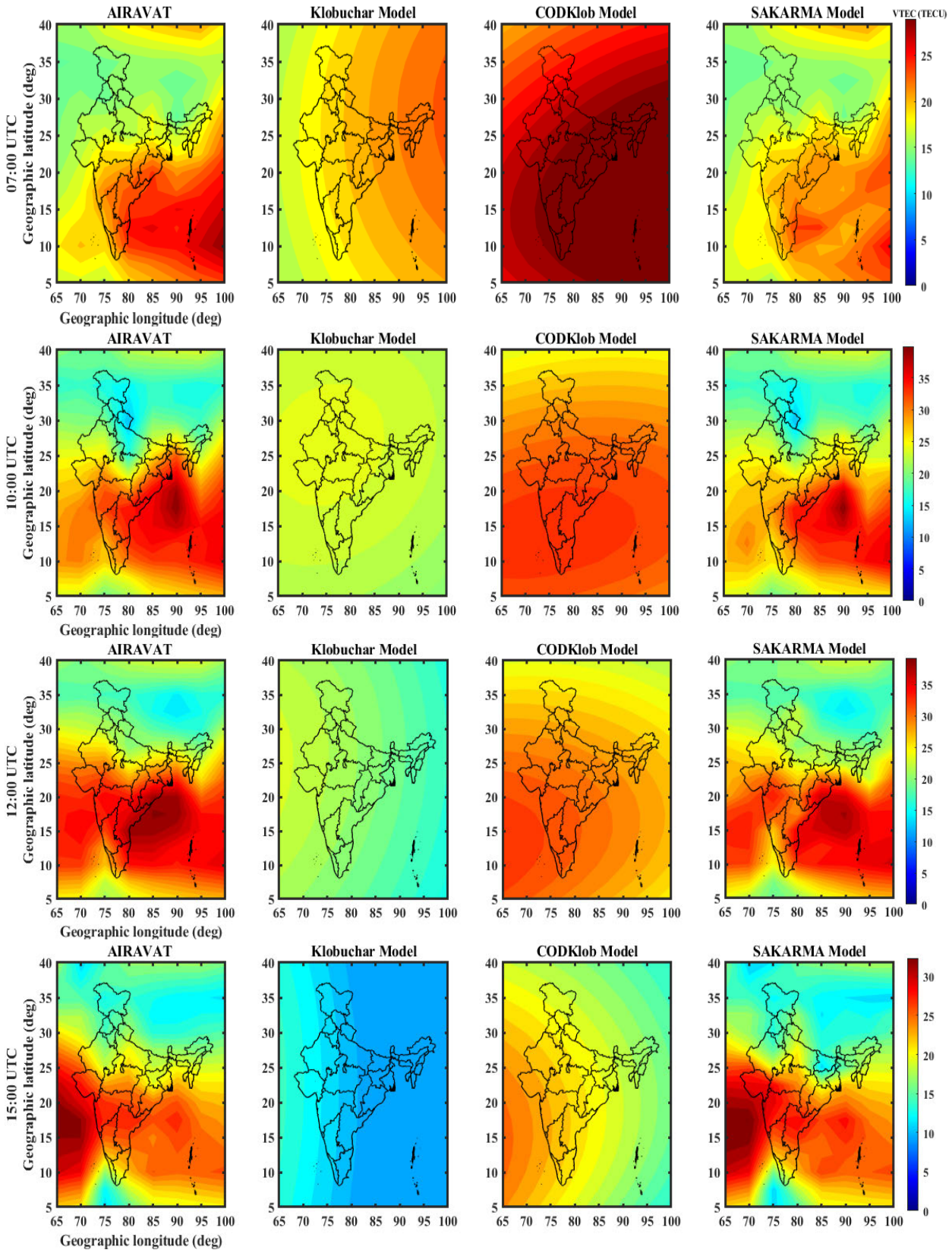

FIGURE 2. The performance validation of SAKARMA Model in estimating the ionospheric delays during International Geomagnetic quiet day, 16 September 2016 over Indian region (Colour bar refer to VTEC values in TECU).

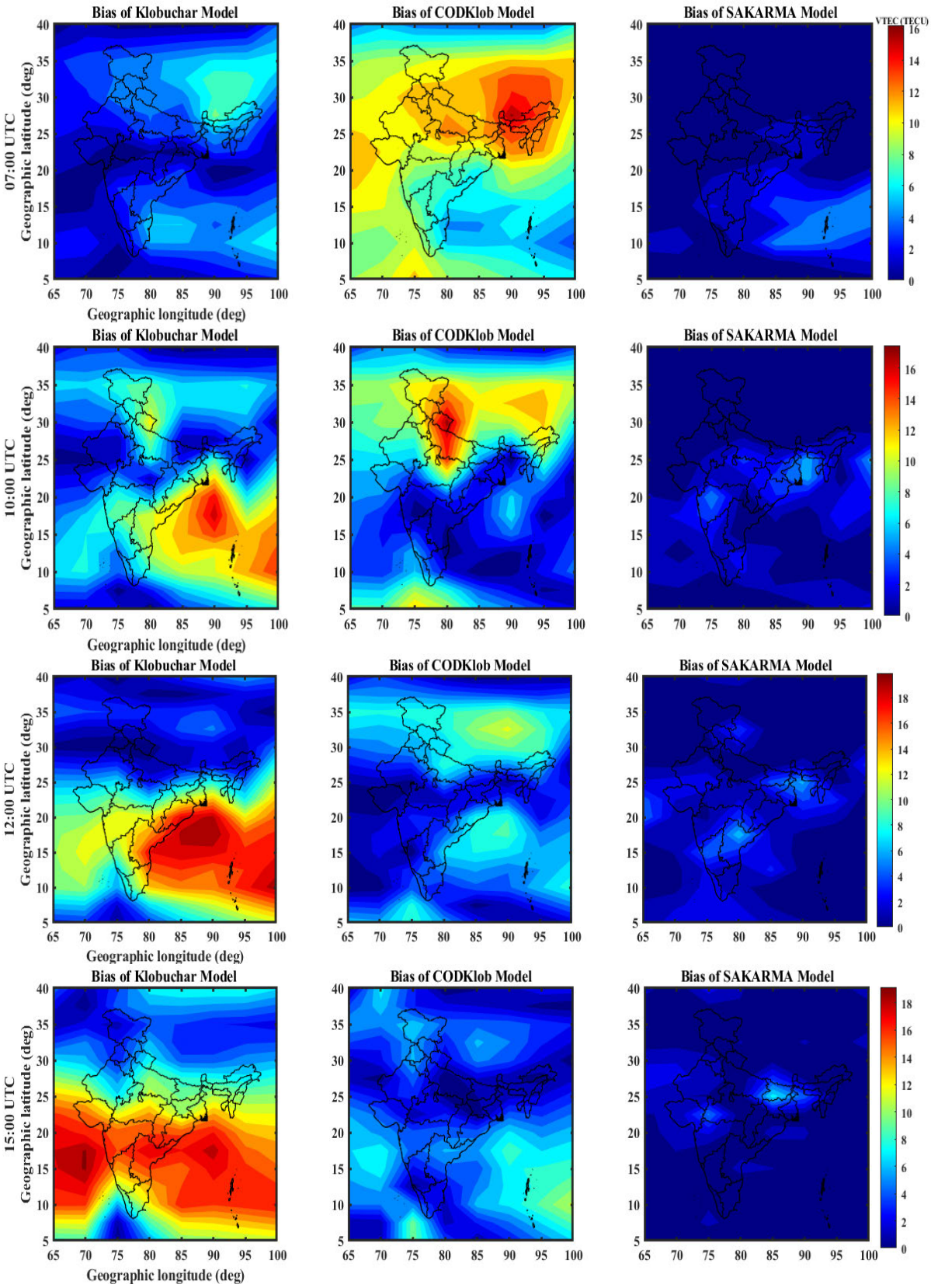

FIGURE 3. The actual absolute differences of Klobuchar, CODKlob and SAKARMA models with AIRAVAT VTEC data in estimating the ionospheric delays during International Geomagnetic quiet day, 16 September 2016 over Indian region (Colour bar refer to VTEC values in TECU).

TABLE 1. Error measurements of SAKARMA model for forecasting ionospheric delays over Indian region.

Model	Quiet Day (16 September 2016)			Disturbed Day (29 September 2016)		
Geomagnetic status	SAKARMA Model	Klobuchar Model	CODKlob Model	SAKARMA Model	Klobuchar Model	CODKlob Model
MAE (TECU)	0.19-2.3	1.7-8.9	2.19-6.56	0.2-1.5	1.3-6.7	2.9-14.47
MSE (TECU)	0.016-13	4.6-121	6.63-68.99	0.11-4.1	3.0-66.9	12.45-295.9
MAPE (%)	5.00	25.8	34.62	5.33	27	59.70

corresponding spatiotemporal VTEC values forecasted by Klobuchar model, CODKlob model and SAKARMA model during a moderate geomagnetic storm (Dst index = −62 nT) on 29 September 2016 over Indian region. The maximum VTEC values (TECU) of AIRAVAT are observed as greater than 30 TECU at 07:00 UTC and 15:00 UTC, 40 TECU at 10:00 UTC and 12:00 UTC hours. But the peak VTEC values are different for different regions over India (Fig. 4). The one day ahead forecasting of the proposed model SAKARMA are closely following the AIRAVAT VTEC patterns as shown in Fig. 4. It is observed from Fig. 4 that VTEC patterns modelled by Klobuchar model are reasonably interpreting the AIRAVAT VTEC patterns at 07:00 UTC, 10:00 UTC, 12:00 UTC and 15:00 UTC hours during storm periods. But VTEC patterns modelled by CODKlob model has shown more VTEC values than AIRAVAT VTEC values for all the UTC hours of study (Fig. 4).

Evidently, it can be inferred from Fig.4 that SAKARMA model has effectively followed the VTEC distributions of AIRAVAT VTEC maps compared to the other two at all the UTC hours considered during storm periods. Fig. 5 delineates the actual absolute differences (bias) of SAKARMA model, Klobuchar model and CODKlob model with AIRAVAT VTEC values in TECU during the moderate storm event on 29 September 2016. Fig.5 most evidently reflects that the bias values of the Klobuchar model with AIRAVAT are more compared to bias values of SAKARMA model at different geographical latitudes and longitudes of Indian Region. Moreover, significant bias values of Klobuchar model with AIRAVAT can be observed in the patch of low latitude from above 10° N to below 20° N with centre at 15° N latitude. CODKlob model has shown more residual values compared to Klobuchar model not only over low latitudes and EIA crest regions but also over beyond the EIA crest regions, i.e. 25-35°N latitudes. The residuals of CODKlob model over EIA and low latitude regions are up to 5-10 TECU whereas beyond the EIA crest it read more than 15 TECU at different UTC hours. As expressed, SAKARMA method performed consistent and adaptive in forecasting the AIRAVAT VTEC patterns for Indian regions during moderate geomagnetic storm either with less bias values of 3 TECU.

Assessment of SAKARMA model in forecasting the latitudinal variation and Equatorial Ionization Anomaly (EIA)

Fig. 6 and Fig. 7 illustrates the latitudinal contour plot of SAKARMA model and Klobuchar model in forecasting the AIRAVAT VTEC values with respect to 0-23 UTC hours from nearby equator (5° N) to latitudes beyond the EIA crest (40° N) at 80° E longitude during both the typical geomagnetic quiet and disturbed days respectively. The corresponding forecasting errors of the Klobuchar model, CODKlob model and improved Klobuchar model (proposed SAKARMA model) are also depicted in Fig. 6 and Fig. 7 over the Indian region during both geomagnetic quiet and disturbed days respectively. A careful study of the AIRAVAT VTEC contour plot in Fig. 6, helps us observe that the EIA effects are non-existent between 17:00 UTC and 03:00 UTC hours. However, the anomalies become noticeable at around 05:00 UTC hours, reached their major peak at around 10:00 UTC hours and slowly subsided during pre-sunset 13:00 UTC hours. Fig. 6, also presents the bias plots of the SAKARMA, Klobuchar and the CODKlob models. Klobuchar model moderately estimated the EIA features between 10:00 and 15:00 UTC hours resulting in the bias ranging from 6-18 TECU. Similarly, CODKlob model also moderately estimated the latitudinal ionospheric delays over the Indian region resulting in the bias values ranging between 8-18 TECU. Nevertheless, SAKARMA model succeeded in forecasting the EIA TEC features with very less bias values of the range 2-4 TECU.

In the case of AIRAVAT VTEC values during the moderate storm occurred on 26 September 2016 as shown in Fig. 7, the TEC anomalies become noticeable around 05:00 UTC hours, reaches a major peak at around 08:00 UTC hours and subsides during pre-sunset to a minor peak at 12:00 UTC hours. Klobuchar model results in higher bias values at low latitudes ranging from 13°N to 25°N between 5 UTC hours to 18:00 UTC hours. CODKlob model has shown larger residuals over beyond EIA crest region compared to the low latitude EIA region. However, SAKARMA model unlike Klobuchar and CODKlob models, performed great during the disturbed ionospheric condition resulting less forecasting error with

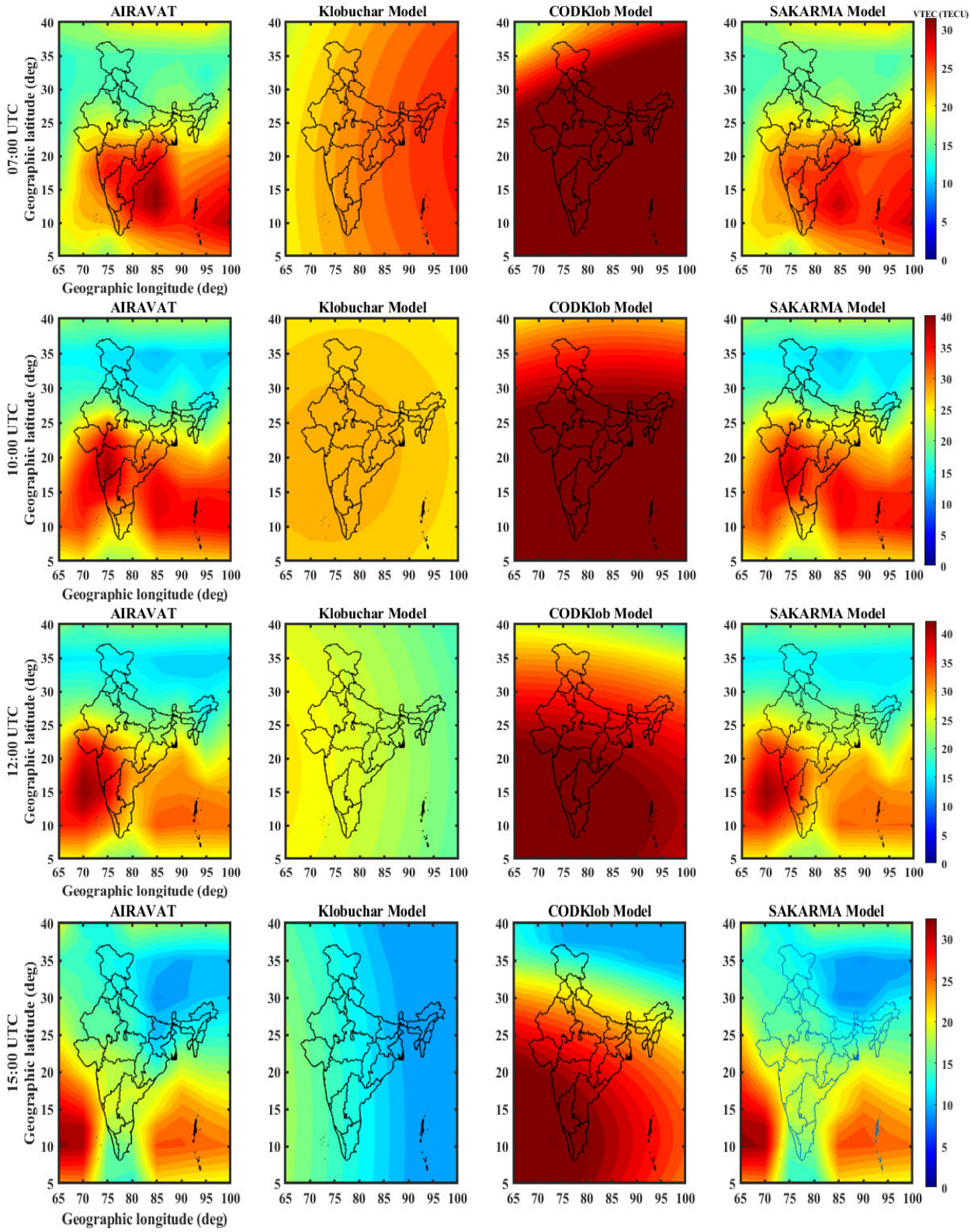

FIGURE 4. The performance validation of SAKARMA Model in estimating the ionospheric delays during International Geomagnetic disturbed day, 29 September 2016 over Indian region.

bias values of 4-7 TECU during 06:00 UTC hours over 15°N to 25°N. (Fig. 7).

Furthermore, to evaluate the forecasting accuracy of the SAKARMA, Klobuchar and CODKlob models, the RMSE

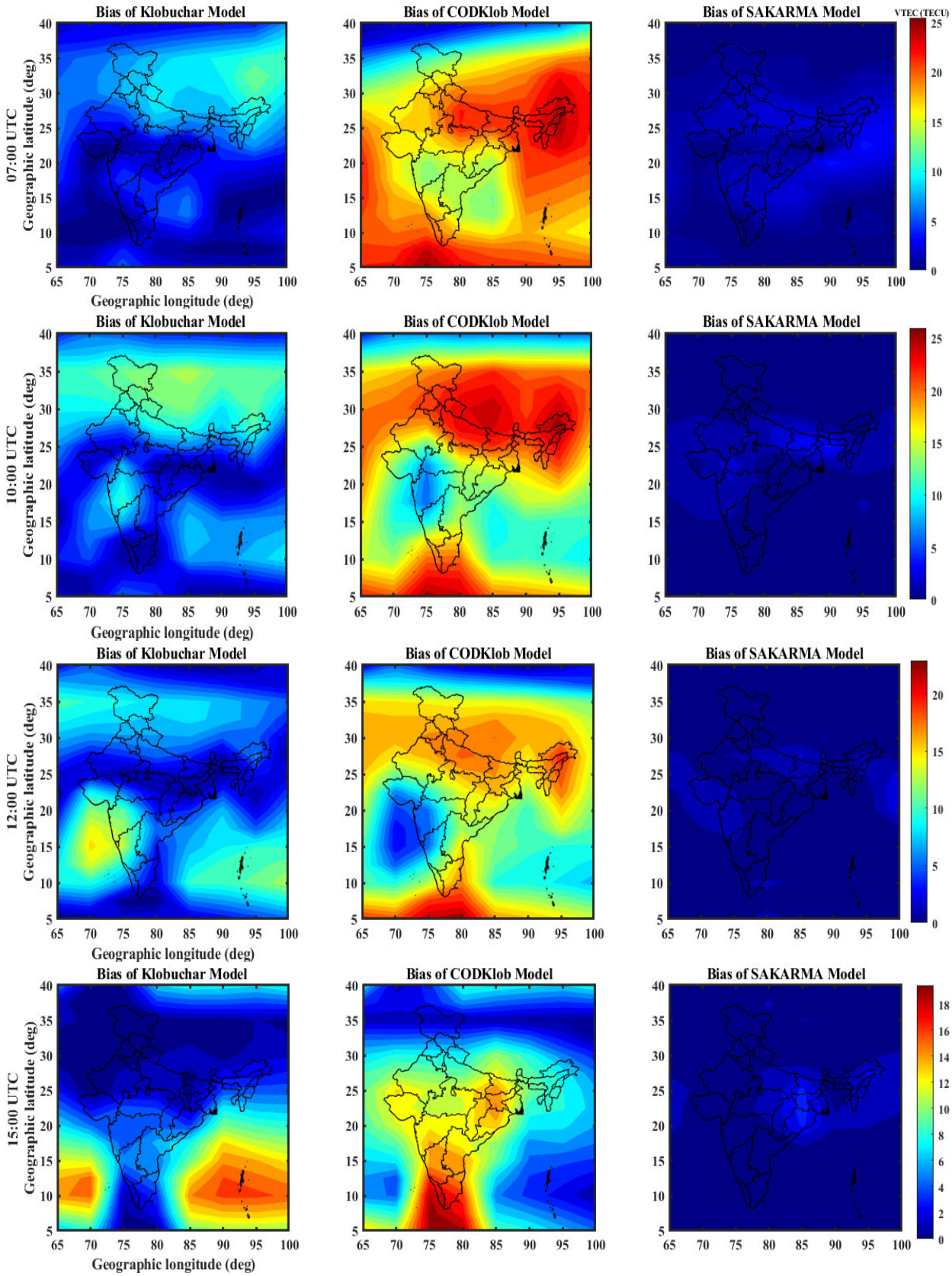

FIGURE 5. The actual absolute differences of Klobuchar, CODKlob and SAKARMA models with AIRAVAT VTEC data in estimating the ionospheric delays during International Geomagnetic disturbed day, 29September 2016 over Indian region (Colour bar refer to VTEC values in TECU).

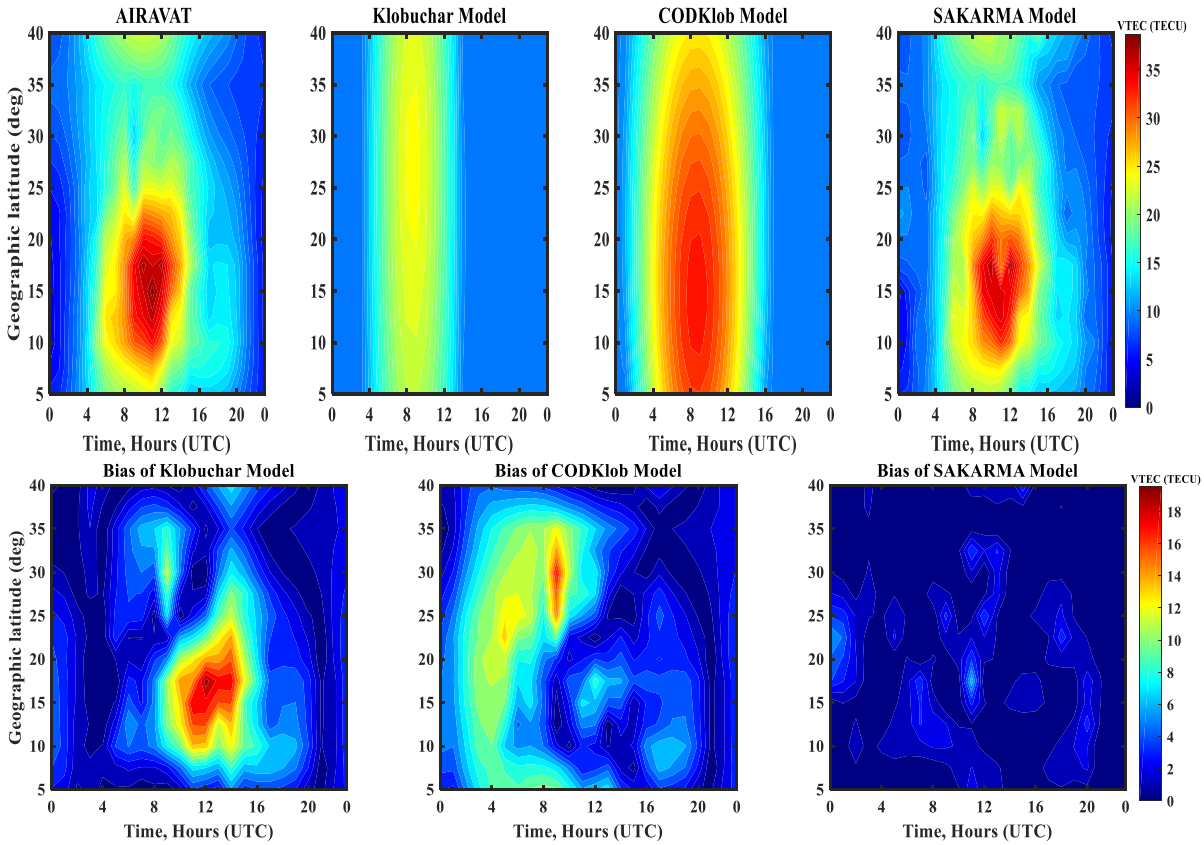

FIGURE 6. The latitudinal EIA features forecasted by SAKARMA model during geomagnetic quiet day, 16 September 2016.

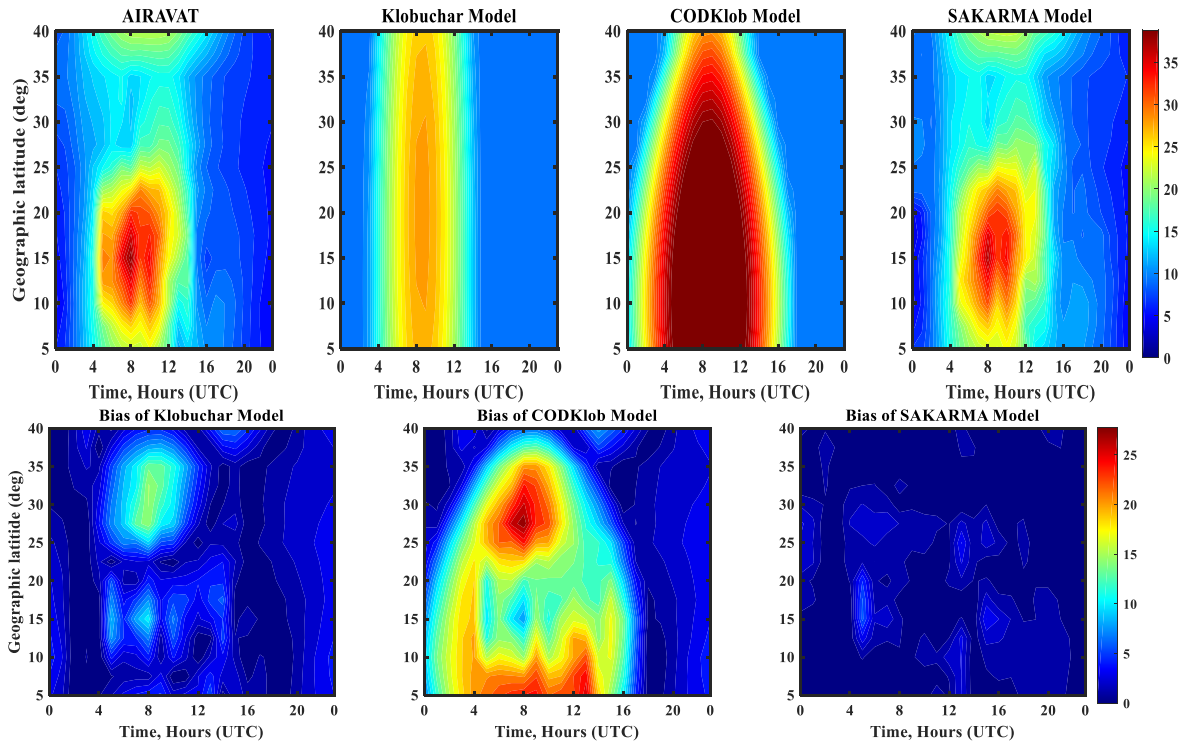

FIGURE 7. The latitudinal EIA features forecasted by SAKARMA model during geomagnetic disturbed day, 29 September 2016.

values, goodness of fit (R^2) and correlations of VTEC data forecasted using SAKARMA, Klobuchar model and CODKlob model with AIRAVAT VTEC data are investigated during both geomagnetic quiet and disturbed day; the plots of

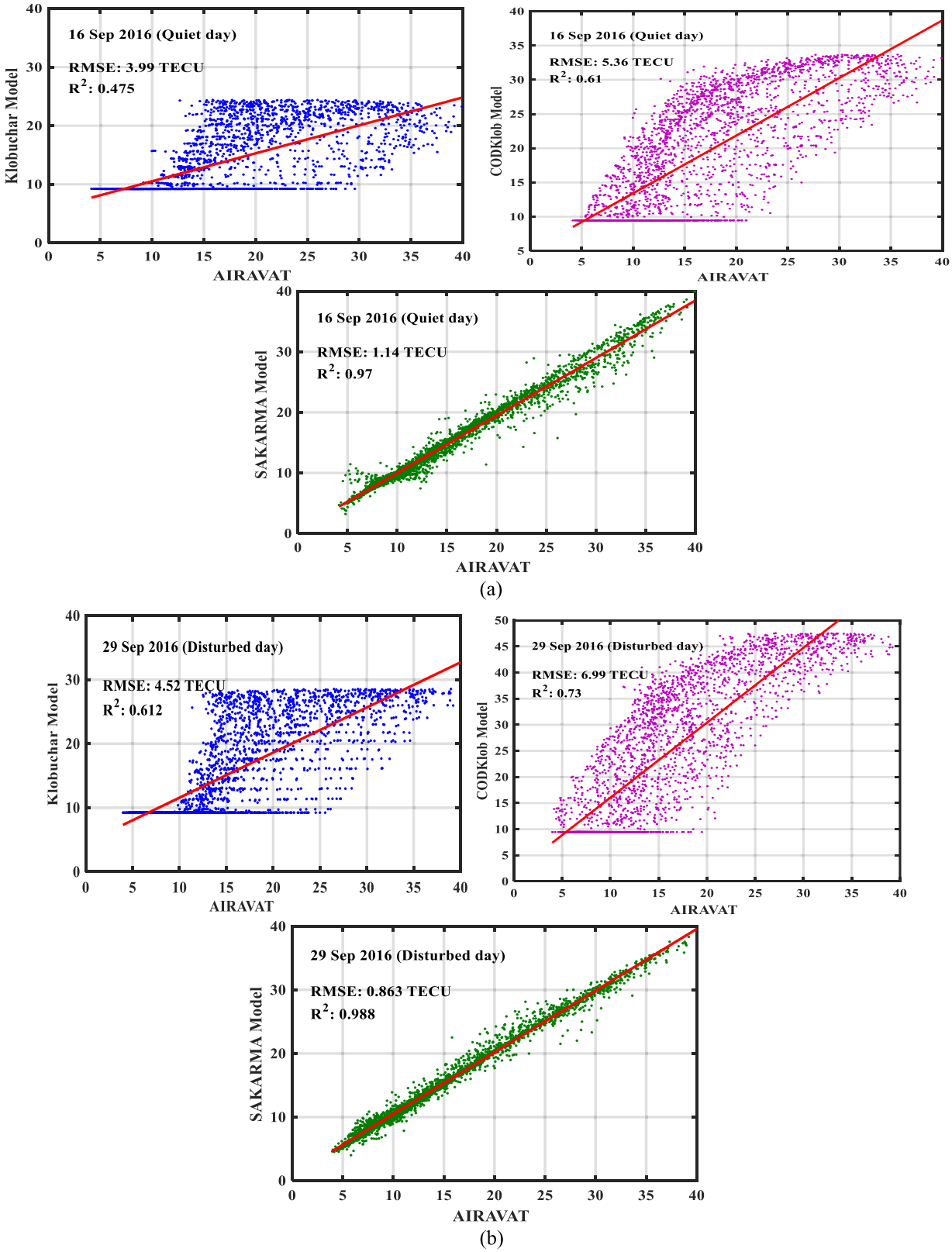

FIGURE 8. The correlation plot between AIRAVT and SAKARMA model, Klobuchar model during (a) geomagnetic quiet day, 16 Sep 2016 and (b) (a) geomagnetic disturbed day, 29 Sep 2016.

which are presented in Fig. 8. It is observed that SAKARMA model resulted in an RMSE of 1.14 TECU and 0.863 TECU during geomagnetic quiet day and disturbed day respectively. The RMSE values of the Klobuchar model read 3.99 TECU

and 4.52 TECU during geomagnetic quiet day and disturbed day respectively indicating its underperformance compared to SAKARMA model. The R^2 -values ofSAKARMA model, Klobuchar model and CODKlob model measured 0.97, 0.47 and 0.61 during geomagnetic quiet day and 0.98, 0.61 and 0.73 during geomagnetic disturbed day respectively. Thus, it is observed that the models have improved correlation values during disturbed day but high RMSE value is recorded for Klobuchar model and CODKlob model. Therefore, SAKARMA model is more suitable for the single frequency GNSS/NavIC users to provide one day ahead ionospheric corrections over Indian region.

Performance Assessment of SAKARMA using NAVIC data at a low latitude geographical location: latitude 16.37^o N and longitude 80.37°E:

The dual frequency (L5 and S band) NavIC receiver located at K L E F, Vaddeswaram, Guntur station (geographic: 16.37°N, 80.37°E; geomagnetic: 7.44°N, 153.75°E), India is chosen for data collection. The Receiver Independent Exchange (RINEX) files, PRN codes, azimuth angle, elevation angle, slant TEC, carrier phase and pseudo range measurements are extracted from NavIC dual frequency receiver for the period from 2 -12 September 2017. In order to obtain the data sets of VTEC values estimated by Klobuchar model during the period of investigation, the required inputs (Eq. 2) for Klobuchar model are driven from GPS navigation message files from NavIC receiver. Fig. 9 (top panel) shows comparison between the observed NavIC vertical TEC (VTEC) data sets (obtained using Eq. 4) and Klobuchar modelled daily VTEC values during 2-12 September 2017. The bottom panel of Fig. 9 shows the residual VTEC time series derived by subtracting Klobuchar model estimated delays from NavIC measured delays (Eq. 5) during the period of investigation. It is observed from Fig. 9 that the time series of Klobuchar model residuals exhibit two maxima per day due to cosine-based model to represent the daily peak ionospheric TEC variation at around 14.00 local time and night time delay constant [9]. However, the residual is not systematic and the residual is non-stationary time series which could be ascribed to the anomalies in the Klobuchar coefficients [7]. Moreover, residual term variations could also be impacted by the level of solar and geomagnetic activity components contributed to ionospheric TEC variations [4], [17]. Hence, the performance of the proposed SAKARMA model is validated during both geomagnetic quiet and disturbed days in 2017 year.

Fig. 10 shows the Disturbed storm time (Dst) index variations which reflects the disturbed (<-50 nT) and quiet (>-50 nT) geomagnetic activity conditions due to high- and low-level solar activity, respectively during 2 - 12 September 2017. A Sudden Storm Commencement (SSC) during early UT hours on 7 September 2017 is noticed and then a sudden decrease in the Dst index values reached to the minimum values of -142 nT in the early UT hours on 8 September 2017 which refers to a strong geomagnetic storm (shown in red dot line in Fig. 10). The storm has recovered

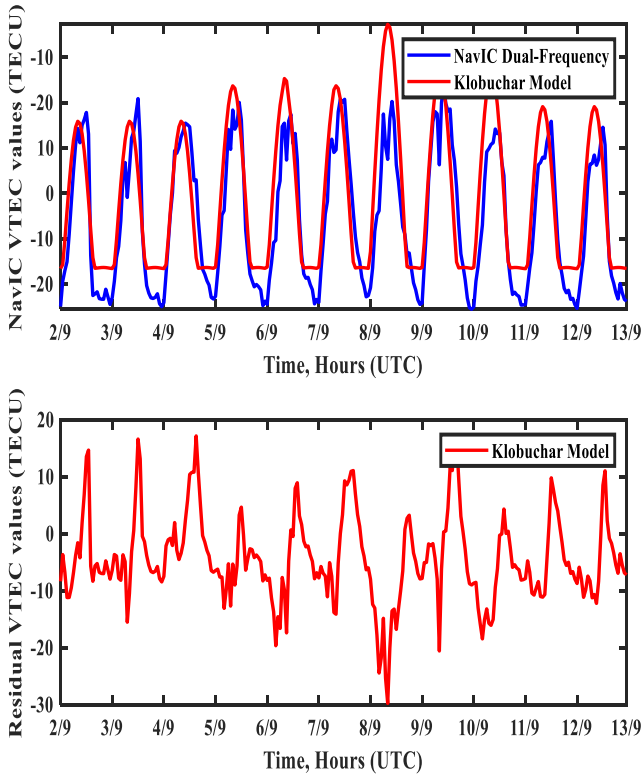

FIGURE 9. The VTEC values estimated from NavIC receiver measurements, Klobuchar model estimated VTEC values (top panel) and the estimated residuals of the Klobuchar model (bottom panel).

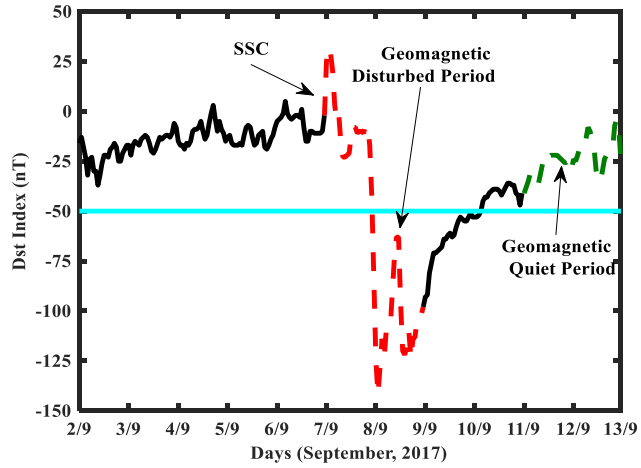

FIGURE 10. DST index of September 2017 with geomagnetic disturbed and quiet days.

completely during 11-12 September 2017 with minimum Dst index values (shown in green dot lines in Fig. 10).

In order to validate the performance of proposed SAKARMA model, the residual VTEC time series of 264 values for 11 days during investigation period obtained from Eq. 5 are used. The two test cases considered to validate the SAKARMA model are stated below and listed in Table. 2.,

A. Firstly, during geomagnetic quiet days (with reference to Fig. 10), 11 September 2017 and 12 September 2017 followed by second case,

TABLE 2. Assignment of input datasets to SAKARMA model in 2017 for NAVIC data.

Period of investigation	Training period (September 2017)	Testing period (September 2017)
Disturbed days	2-6	7
	2-7	8
Quiet Days	2-10	11
	2-11	12

B. During strong geomagnetic storm days (with reference to Fig. 10), 7 September 2017 and 8 September 2017

In order to forecast the VTEC values during 7 September 2017 (test period, geomagnetic storm day), the values obtained from Eq. 5 during 2 September to 6 September 2017 are considered during training period of SAKARMA model. The training period from 2 September to 7 September 2017 is considered to test the SAKARMA model on 8 September 2017 (test period). Similarly, to test the proposed model during 11 September 2017 (geomagnetic quiet day), the training period for SAKARMA model is 2 September 2017 to 10 September 2017. Likewise, SAKARMA model is also tested on 12 September 2017 (geomagnetic quiet day) with the training period as 2 September 2017 to 11 September 2017.

A. SAKARMA MODEL PERFORMANCE DURING GEOMAGNETIC QUIET DAYS (11 AND 12 SEPTEMBER 2017)

The performance of VTEC forecasting models, such as, the proposed SAKARMA model and Klobuchar model, has been analysed during geomagnetic quiet days (11 and 12 September 2017) as per the criteria of training and testing period data sets mentioned in Table. 2. The diurnal variations of VTEC values estimated from measurements of NavIC receiver along with the VTEC values forecasted by Klobuchar model and SAKARMA model during the geomagnetic quiet days have been illustrated in Fig. 11 and Fig. 12 (left panels). The comparison for residuals of the Klobuchar and SAKARMA models are shown in Fig. 11 and Fig. 12 (right panels).

Fig.11 shows the diurnal variation of the VTEC values measured from NavIC observations. Fig. 11 shows that the VTEC values forecasted using SAKARMA model are in good agreement with the VTEC values measured from NavIC observations and following the diurnal temporal variations very closely than the Klobuchar model estimated values during 11 September 2017. The differences (residual) between

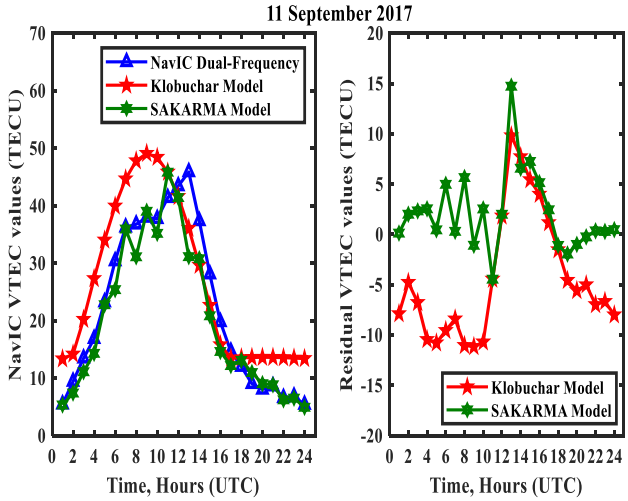

FIGURE 11. Testing of Klobuchar and SAKARMA models for quiet day 11September 2017 with corresponding estimated VTEC residuals.

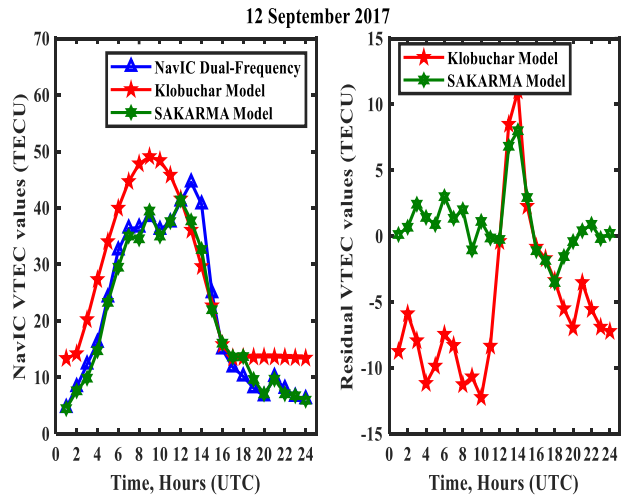

FIGURE 12. Testing of Klobuchar and SAKARMA models for quiet day 12 September 2017 with corresponding estimated VTEC residuals.

the proposed model and NavIC measured VTEC values are within the range of ±5 TECU, whereas, for Klobuchar model the residuals read ±10 TECU, showing large deviations of model observations during geomagnetic quiet day, 11 September 2017 compared to SAKARMA model (Fig. 11, right panel).

Fig. 12 shows the effectiveness of the SAKARMA model performance in capturing the diurnal patterns contained in measured VTEC values from NavIC observations during the respective geomagnetic quiet day, i.e. 12 September 2017. It is observed that the SAKARMA model has followed the NavIC VTEC patterns accurately while the Klobuchar model produced a smooth curve due to its peak value of cosine function on 12 September 2017 (Fig. 12, left panel). The temporal resolution of SAKARMA model is better with less VTEC residuals than Klobuchar model as reported from the Fig. 12 (right panel).

The measurement error values such as MAE, MSE, MAPE and RMSE values for the corresponding geomagnetic quiet

TABLE 3. Error measurements of SAKARMA model for estimating and forecasting VTEC during geomagnetic quiet days.

Geomagnetic status Day of test	Geomagnetic Quiet days			
	11 September		12 September	
Model	Klobuchar	SAKARMA	Klobuchar	SAKARMA
MAE (TECU)	6.83	2.91	6.90	1.76
MSE (TECU)	55.83	19.01	59.00	6.93
MAPE (%)	47.56	12.42	50.12	9.14
RMSE (TECU)	7.47	4.36	7.68	2.63

days are tabulated in Table. 3. It is observed from the MAPE values during the geomagnetic quiet days, that the Klobuchar model is 50-52 % accurate while SAKARMA model is 88-91 % accurate in forecasting the VTEC values. Moreover, from Table. 3, it is determined that MAE values are 2.91 TECU and 1.76 TECU for SAKARMA model; 6.83 TECU and 6.90 TECU for Klobuchar model and the MSE values are 55.83, 59 TECU for Klobuchar model and 19.01, 6.93 TECU for SAKARMA model during 11 September 2017 and 12 September 2017 respectively. Moreover, RMSE values read 7.47, 7.68 TECU for Klobuchar model and 4.36, 2.68 TECU for SAKARMA model during 11 September 2017, 12 September 2017 respectively (Table 3). However, it's crucial to validate the SAKARMA model during the disturbed geomagnetic/high solar activity conditions.

B. SAKARMA MODEL PERFORMANCE DURING GEOMAGNETIC STORM DAYS (7 AND 8 SEPTEMBER 2017)

The Fig. 13 shows the comparison of Klobuchar model and SAKARMA model in capturing the temporal variations of measured VTEC values from NavIC receiver during the testing days, 7 and 8 September 2017. The training data sets for SAKARMA model to validate its effectiveness during the pre-geomagnetic storm day, i.e. 7 September 2017 is as shown in Table. 3. The ionospheric delay values are forecasted during 7 September 2017 using SAKARMA proposed methodology discussed in Section 2 and Fig. 1. The coefficients of SAKARMA model are used to estimate and forecast the pre-storm and storm day VTEC values one day ahead. Similarly, the SAKARMA model is also applied to forecast the ionospheric delays on 8 September 2017, which is a geomagnetically strong disturbed day (Fig. 10) as per Table. 2.

It is observed from Fig. 13 (top panel) that when compared with the estimated VTEC values from NavIC measurements, Klobuchar model has shown large deviations of 10- 30 TECU (overestimations during peak periods of UT hours, ∼8-10 UTC) and fixed values at night UTC

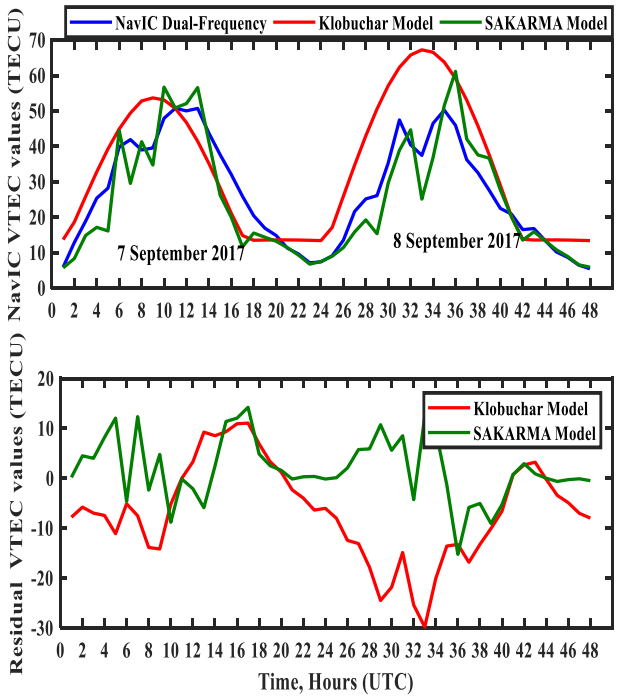

FIGURE 13. Testing of Klobuchar and SAKARMA models for disturbed days 7 and 8 September 2017 with corresponding estimated VTEC residual values.

hours over the Guntur station during both the pre storm (7 September 2017) and storm day (8 September 2017). In contrast, SAKARMA model has followed temporal local variations of the measured NavIC VTECvalues better than Klobuchar model during both the geomagnetic disturbed days (Fig. 13, top panel). Moreover, the VTEC residual of the models shown in Fig. 13 (bottom panel) delineates that SAKARMA model has comparatively 5-10 TECU of less forecasting error than Klobuchar model during 7 September 2017 and 10-20 TECU of less forecasting error during 8 September 2017. Thus, unlike Klobuchar model, the proposed SAKARMA model is providing accurate local day time temporal ionospheric variations and night hours variations.

In addition, Table. 4 has shown that the error measurement values of SAKARMA model are far less than the Klobuchar model during the disturbed geomagnetic conditions. The MAE values of SAKARMA model 1.97 TECU and 7.43 TECU are less than Klobuchar model during pre-storm day and storm day respectively (Table. 4). Similarly, MSE values of proposed model are 16-170 TECU less than Klobuchar model. The MAPE values of Klobuchar model are 34.67 % and 53 %, while 17.44 % and 15.63 % for SAKARMA model, which shows that SAKARMA model is 17-37 % more accurate in forecasting the ionospheric delays during the disturbed geomagnetic conditions in 2017 than Klobuchar model (Table. 4). Though, the accuracy of both the models are affected during storm period, SAKARMA model is providing better forecast of ionospheric delays compared to Klobuchar model. Nevertheless, it is observed that

TABLE 4. Error measurements of SAKARMA model for estimating and forecasting VTEC during geomagnetic disturbed days.

Geomagnetic status Day of test	Geomagnetic Disturbed days			
	7 September		8 September	
Model	Klobuchar	SAKARMA	Klobuchar	SAKARMA
MAE (TECU)	6.97	5.0	12.12	4.69
MSE (TECU)	61.56	45.29	210.73	40.35
MAPE (%)	34.67	17.44	53.00	15.63
RMSE (TECU)	7.84	6.73	14.51	6.35

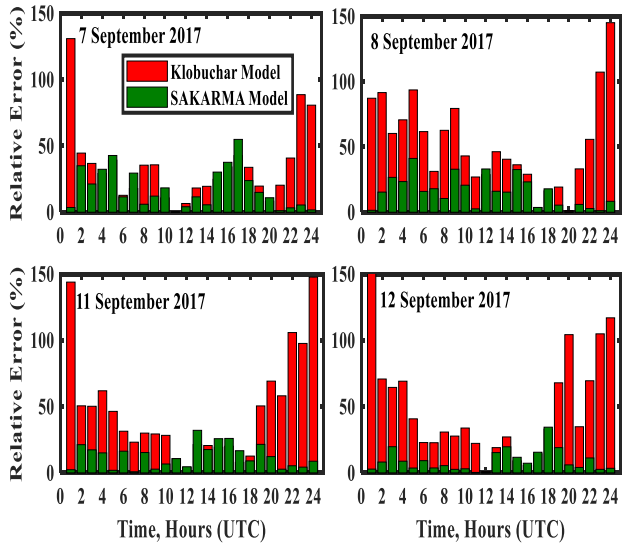

FIGURE 14. The relative errors calculated for SAKARMA and Klobuchar models during geomagnetic quiet and disturbed days in 2017 year (Table. 2).

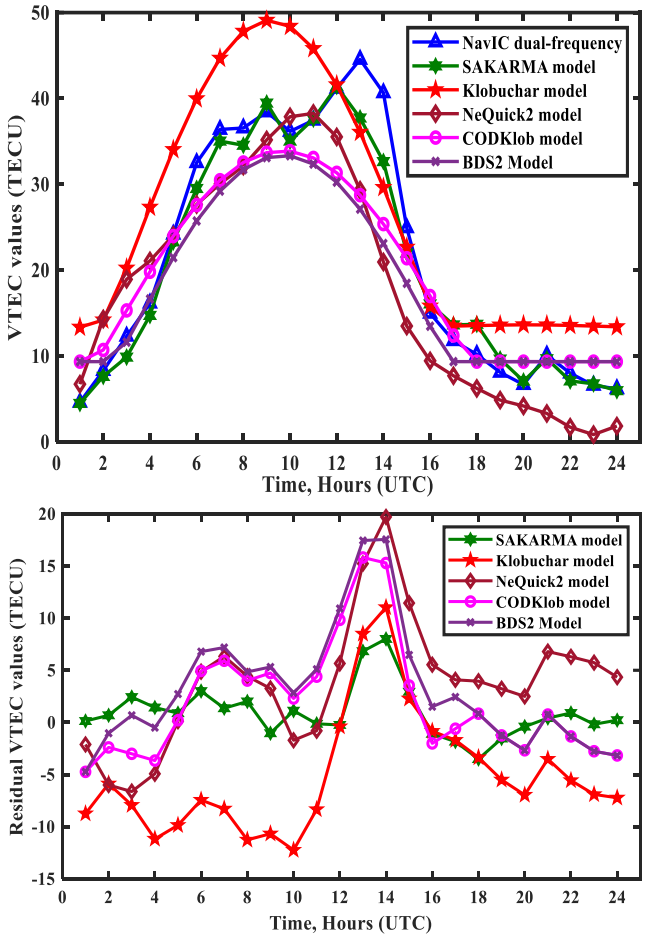

FIGURE 15. The comparison of hourly VTEC values estimated from NavIC measurements and forecasted VTEC values using proposed model, Klobuchar model, NeQuick2 model, CODKlob Model and BDS 2 model during 12 September 2017 over EIA region Guntur (top panel) and error of the models in estimating the NavIC signal delays (bottom panel).

SAKARMA model forecasting accuracy is influenced during geomagnetic disturbed days compared to the geomagnetic quiet days (Table. 3 and Table. 4).

Further, the relative errors of SAKARMA and Klobuchar models have been measured during both the quiet (11 and 12 September 2017) and disturbed (7 and 8 September 2017) geomagnetic conditions in the investigation period of 2017. It is observed from Fig. 14 (top panels and bottom panels) that the distribution of relative errors for SAKARMA model are relatively less than the Klobuchar model. Nonetheless, the relative errors during 12-18 UTC hours for both the models are approximately similar and in the range of 20-40%. It is clearly seen that the relative errors during 8 September 2017 for both models are comparatively more than the relative errors during 7 September 2017 and 11, 12 September 2017 (Fig. 14). However, the proposed SAKARMA model have 20-70% of less relative errors than Klobuchar model during 8 September 2017 (Fig.14). It is noticed that the relative errors for SAKARMA model are comparatively less during geomagnetic quiet days than geomagnetic disturbed days. However, the relative errors of Klobuchar model during both geomagnetic quiet and disturbed days are far more than SAKARMA model (Fig. 14).

Moreover, the performance of proposed SAKARMA model is also validated with other broadcasted models used for single frequency users, such as Klobuchar-style coefficients provided by the Center for Orbit Determination in Europe (CODE) (CODKlob) Model, BeiDou System (BDS2) Model and NeQuick 2 Model over a low latitude NavIC station at KLEF, Guntur, India during 12 September 2017 (a geomagnetic quiet day) as shown in Fig. 15. It is observed that the hourly (diurnal) ionospheric time delay values estimated from NavIC measurements are minimum during 1-3 UTC hours (top panel of Fig. 15). The broadcast models are in good agreement with the NavIC measured VTEC values. However, the ionospheric broadcast models are reasonably good in following the diurnal patterns of low latitude ionospheric delays estimated from NavIC measurements, more deviations are observed during the mid- day hours and during post-sunset. The sharp increase of the ionospheric

TABLE 5. Error measurements of SAKARMA model, and other broadcast models in estimating and forecasting ionospheric delay during geomagnetic quiet day 12 September 2017.

Parameter of Analysis/Model	MAE (TECU)	MSE (TECU)	MAPE (%)	RMSE (TECU)
SAKARMA model	1.76	6.93	9.14	2.63
Klobuchar model	6.90	59.00	50.12	7.68
NeQuick2 model	5.60	50.25	37.32	7.08
CODKlob model	4.17	33.33	23.47	5.77
BDS2 model	4.61	42.75	23.79	6.53

delays from 15 TECU to 36 TECU during 4-9 UTC hours respectively could not be estimated by the broadcast models. During 6-10 UTC hours except the SAKARMA model, the remaining models are underestimating (NeQuick 2 model, CODKlob model and BDS2 model) and overestimating (Klobuchar model). It is also noticed that during 15-17 UTC hours, the proposed model and broadcast models are in good agreement with the NavIC measured VTEC values compared with the other broadcast models. However, the SAKARMA model and the broadcast models such as CODKlob model and BDS2 model are in good agreement during 18-24 UTC hours, whereas deviations are observed with NeQuick 2 model (underestimating) and Klobuchar model (overestimating) as depicted from top panel of Fig. 15. Moreover, it can be noticed that the ionospheric delay estimations of CODKlob model and BDS2 model are close to one another during 18-24 UTC hours.

The Fig. 15 (bottom panel) illustrates the hourly differences of the proposed model and broadcast models during the geomagnetic quiet day, 12 September 2017. Compared to the measured VTEC values from NavIC observations, Klobuchar model present more negative deviations (overestimations) of −5 to −12 TECU and positive deviations (underestimations) of 2–20 TECU are observed with NeQuic2 model, CODKlob model and BDS2 model. However, the forecasted VTEC values of proposed SAKARMA model are in good agreement with the measured ionospheric delays with very less negative (−1 to −3 TECU) and positive (0.13-8 TECU) deviations compared to the ionospheric broadcast models (Fig. 15 (bottom panel)). Furthermore, Table 4 shows the calculated error measurements of different broadcast models and proposed SAKARMA model with respect to estimated VTEC values from NavIC measurements. Comparing the SAKARMA model performance during quiet day (test period) on 12 September 2017, the MAE, MSD, MAPE and RMSE values of other broadcast models used for single frequency users are larger than the proposed model as shown in Table 5. SAKARMA model presents better performance followed by CODKlob model, BDS2 model, NeQuick2 model and Klobuchar model. It is also observed that Klobuchar model, Nequick2 model and BDS2 model have larger MAE, MSD, MAPE and RMSE values compared to CODKlod model. It is noticed that SAKARMA model is 91% accurate, CODKlob model and BDS2 models are 77 % accurate followed by NeQuick 2 model with 63 % while Klobuchar model with 50% of accuracy during geomagnetic quiet day, 12 September 2017.

It can therefore be duduced that SAKARMA model can be considered as a more suitable ionospheric model for single frequency users capable of providing 83-91 % accuracy during both geomagnetic quiet and disturbed conditions over low-latitude Equatorial Ionization (EIA) region, Guntur, India (Table. 3). Unlike, NavIC systems that use grid-based models for ionospheric corrections, the coefficients-based techniques are more reliable in real-time single frequency user services due to their simplicity and applicability.

IV. CONCLUSION

Developing/improving the performance of ionospheric broadcasting models to alert and correct the ionospheric corrections is crucial for the real-time single frequency GNSS/NavIC users. The anomalies in ionospheric delays exhibit complex patterns and cannot be estimated using global empirical models especially over low-latitude regions such as India. In this paper, a new ionospheric model for **S**ingle Frequency GNSS User **A**pplications using **K**lobuchar model driven by **A**uto **R**egressive **M**oving **A**verage (SAKARMA) method is proposed. The SAKARMA model performance is tested in estimating and forecasting the ionospheric delays over Indian region. AIRAVAT hourly VTEC maps developed using 26 GPS stations data for a month of September 2016 over Indian region has been considered in the present work. The proposed SAKARMA model has been tested and validated with Klobuchar model and modified Klobuchar like model, CODKlob model during geomagnetic quiet and disturbed days in September 2016. It is observed that SAKARMA model exhibits consistent accuracy of 95% and MAE of 1.5 TECU in forecasting the ionospheric delays during all the geomagnetic conditions and in estimating the EIA patterns as well over Indian region. Klobuchar model and CODKlob model are comparatively reasonable over Indian region with MAPE values of 25-27% and 34.62-59.7% values during geomagnetic quiet and disturbed ionospheric conditions. It is evident from the experimental results, the SAKARMA model is performing well with consistency in the forecasting accuracy.

Further, SAKARMA model performance is also validated over low latitude EIA NavIC station, Guntur, India for both geomagnetic quit and disturbed conditions in 2017 year. It is observed that the one day ahead forecast results of SAKARMA model are in good agreement with measured NavIC ionospheric delays compared to existing ionospheric correction models such as NeQuick 2 model, BDS2 model and CODE Klob model. It is observed that the global ionospheric broadcast models are reasonable for estimating the low latitude ionospheric delays for NavIC satellites. However, the accuracy of proposed SAKARMA model is 14 % more than CODKlob model and BDS 2 model, 28% more than NeQuick2 model during geomagnetic quiet day, 12 September 2017. The forecasting accuracy of SAKARMA

model is 83-85% during the geomagnetic disturbed days and is 88-91% during the geomagnetic quiet conditions with MAE of 1.7- 5 TECU.

In future, the research tasks aimed are, the proposed model could be implemented for long term forecasting by using more number of NavIC/GNSS stations from various geographical regions. Various investigators have been working with data-driven machine learning algorithms to estimate and forecast the ionospheric delays [32]. The machine learning algorithms could also be used to improve the ionospheric weather forecasting accuracy while considering ionospheric influencing parameters from the solar and geomagnetic activities.

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