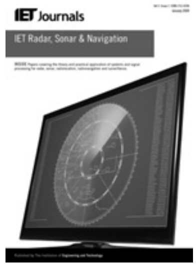
Published in IET Radar, Sonar and Navigation
Received on 11th December 2011
Revised on 18th August 2012
Accepted on 7th September 2012
doi: 10.1049/iet-rsn.2011.0371



ISSN 1751-8784

Approach for near-real-time prediction of ionospheric delay using Klobuchar-like coefficients for Indian region

Ashish Kumar Shukla, Saurabh Das, Atul P. Shukla, Vilas S. Palsule

Space Applications Centre, Indian Space Research Organization, Ahmedabad 380015, India
E-mail: aashishkshukla2002@yahoo.co.in

Abstract: Currently, global positioning system (GPS) satellites transmit the Klobuchar coefficients to estimate ionospheric delay for the single-frequency users. These coefficients are broadcast to the users on the basis of seasonal ionospheric variations and average solar flux. In low-latitude Indian region, prediction of the delay using these coefficient is not accurate because of complex behaviour of the ionospheric. In this study, new Klobuchar-like cofficients are generated using regional total electron content data collected from the 18 stations in Indian. Using these coefficients, a novel approach for near-real-time prediction of the ionospheric delay (for every 5 min) is proposed. This approach provides the opportunity to generate the Klobuchar-like coefficients using shorter data sets (1 day) rather than using long-term statistics of several years, as done in the generation of GPS broadcast Klobuchar coefficients. Performance of the prediction is evaluated for the geomagnetic quiet (A_p index <50) and severely disturbed (A_p index >300) days of 2005 and 2007. Prediction accuracy is significantly improved using the single-frequency users of the Regional Navigational Satellite Systems, such as the proposed Indian Regional Navigation Satellite System.

1 Introduction

Satellite-based navigation systems depending on global positioning system (GPS) suffer by the ionospheric delay. The speed of the propagation of a radio signal in the ionosphere depends on the number of free electrons in its path, known as the total electron content (TEC). TEC is defined as the number of electrons in a tube of 1 m^2 cross-section extending from the receiver to the satellite [1]. The ability to predict the TEC in real time on a global or regional scale is of great value for the satellite navigation. There are several ionospheric models currently being studied and developed. Out of these, the main models are the grid-based single-shell model [2–4], the two-shell model [5] and the Klobuchar model [6]. The Klobuchar model is a simplistic empirical model and is currently being utilised by the GPS users for correcting the ionospheric delay. This model is a trade-off between the ability to model the true ionospheric conditions on the global scale, the minimum number of coefficients to be transmitted by the satellites and also the user computational load [6].

Currently, GPS satellites transmit eight Klobuchar coefficients (four α and four β) for the estimation of the delay by the single-frequency users. There are currently 370 sets of such coefficients, which were generated using the long-term statistics over several years. Selection of the coefficients is done at the GPS Master Control Station and the selected coefficients are placed in the satellite-navigation upload message for downlink to the users. Selection of a set is based on two main criteria: the day of year (37 groupings representing seasonal effects) and the average solar flux value for the previous 5 days (ten groupings). Feess and Stephens [7] compared model values with the actual ionospheric time delay values using dual-frequency GPS receivers and observed that the model leads to an overall reduction in the root-mean-square (RMS) range measurement error of 60%. Although, the accuracy of the Klobuchar model is not very high [6–7], it is still a good option because of its simplicity and the global applicability.

The Klobuchar model is primarily tuned and optimised for the mid-latitude regions [8]. The performance of this model is relatively unknown for the low-latitude regions like India, although there is a good possibility to improve its performance by estimating the coefficients using regional TEC data [6]. India lies in the equatorial ionospheric anomaly (EIA) region, characterised by large TEC gradients, and the TEC maximum in the afternoon hours is often observed $\pm 20°$ on either side of the magnetic equator [9]. Also there are temporal and spatial as well as diurnal and seasonal variations of the TEC, which are neither purely deterministic nor purely random [10].

GPS is currently transmitting the Klobuchar coefficients with a minimum update rate of 1 day [6]. This may not provide consistently accurate delay estimates as there is a large day by day temporal variation of the TEC over the low-latitude Indian region. Modified Klobuchar coefficients generated at a shorter update rate, which will incorporate the short-term variations of the TEC, may be a better option for the Indian region, especially in view of the proposed Indian Regional Navigational Satellite System (IRNSS). Right now, only the wide area augmentation system updates the ionospheric delay information in near-real-time for the single-frequency users [11]. Thus in order to provide a more realistic estimate of the ionospheric delay, in this paper, a novel approach for near-real-time prediction of the ionospheric delay is proposed for the Indian region using the newly generated (Klobuchar-like) coefficients, which are updated at 5 min intervals.

Organisation of the paper is as follows: Section 2 describes the methodology for generation of the Klobuchar-like coefficients and approach for the prediction methodology. Data collection, analysis pre-processing with testing methodology and validation are provided in Section 3. Results and discussion and conclusion are discussed in Sections 4 and 5, respectively.

2 Generation of the coefficients and prediction methodology

2.1 Methodology for generation of Klobuchar-like coefficients

The Klobuchar model is a non-linear model having a cosine representation of the diurnal curve centred about 2:00 pm local time during the day, allowed to vary in amplitude and period, with user latitude; and a constant offset term (5×10^{-9} s) at night [6]. This model is based on the assumption that all the free electrons of the ionosphere are concentrated as a single thin shell at a fixed altitude of 350 km and is given by

$$T_{\text{iono}} = F\left[5 \times 10^{-9} + \sum_{n=0}^{3} \alpha_n \phi_m^n (1 - x^2/2 + x^4/24)\right] |x| < 1.57$$
$$T_{\text{iono}} = F.(5 \times 10^{-9})|x| > 1.57 \quad (1)$$

where

$$x = 2\pi(t - 50\,400) \sum_{n=0}^{3} \beta_n \phi_m^n \quad (2)$$

T_{iono} is the ionospheric delay in seconds, α_n and β_n are the Klobuchar coefficients that are transmitted as a part of the satellite navigation message and 'n' is the degree of polynomial taken as three in the Klobuchar model. ϕ_m is the geomagnetic latitude of the ionospheric pierce point (semicircles). Detailed description of the algorithm is provided in [6].

To generate the new Klobuchar-like coefficients, (1) is linearised using the Taylor series expansion as described in [12].

$$T_{\text{iono}} = T_{\text{iono}}^0 + \sum_{n=0}^{3} \frac{\partial T_{\text{iono}}}{\partial \alpha_n} d\alpha_n + \sum_{n=0}^{3} \frac{\partial T_{\text{iono}}}{\partial \beta_n} d\beta_n \quad (3)$$

Using the broadcasted coefficients as an initial guess (T_{iono}^0), ionospheric delay (T_{iono}) is estimated for all visible satellite paths. These values are used for estimating the error from the measured TEC value (T_{Mes}).

The correction terms $d\alpha_n$ and $d\beta_n$ ($n = 0, 1, 2, 3$) are thus generated by minimising the error norm between the measured and the modelled TEC values as below

$$\begin{bmatrix} \frac{\partial T_{\text{iono}}^1}{\partial \alpha_0} & \cdots & \frac{\partial T_{\text{iono}}^1}{\partial \alpha_3} & \frac{\partial T_{\text{iono}}^1}{\partial \beta_0} & \cdots & \frac{\partial T_{\text{iono}}^1}{\partial \beta_3} \\ \frac{\partial T_{\text{iono}}^2}{\partial \alpha_0} & \cdots & \frac{\partial T_{\text{iono}}^2}{\partial \alpha_3} & \frac{\partial T_{\text{iono}}^2}{\partial \beta_0} & \cdots & \frac{\partial T_{\text{iono}}^2}{\partial \beta_3} \\ \vdots & & \vdots & \vdots & & \vdots \\ \frac{\partial T_{\text{iono}}^k}{\partial \alpha_0} & \cdots & \frac{\partial T_{\text{iono}}^k}{\partial \alpha_3} & \frac{\partial T_{\text{iono}}^k}{\partial \beta_0} & \cdots & \frac{\partial T_{\text{iono}}^k}{\partial \beta_3} \end{bmatrix} \begin{bmatrix} d\alpha_0 \\ d\alpha_1 \\ d\alpha_2 \\ d\alpha_3 \\ d\beta_0 \\ d\beta_1 \\ d\beta_2 \\ d\beta_3 \end{bmatrix} = \begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ B_k \end{bmatrix} \quad (4)$$

Here, $B_i = T_{\text{Mes}}^i - T_{\text{iono}}^{0,i}$ ($i = 1, 2, \ldots, k$, k is the number of the observed satellites) and T_{Mes}^i is the measured TEC and $T_{\text{iono}}^{0,i}$ is the TEC generated using original Klobuchar coefficient for ith satellite. The new Klobuchar-like coefficients are generated using (5) with the help of the measured TEC data and the estimated delay obtained using initial guess. For this, first correction terms $d\alpha_p$ and $d\beta_p$, ($p = 0$, 1, 2, 3) for the specific original Klobuchar coefficients α and β, are generated using 24 h data. The new Klobuchar-like coefficients are obtained by adding the correction terms to the initial guess α and β and are given as below

$$\alpha_{\text{New}}^p = \alpha + d\alpha_p, \quad p = 0, 1, 2, 3$$
$$\beta_{\text{New}}^p = \beta + d\beta_p, \quad p = 0, 1, 2, 3 \quad (5)$$

2.2 Novel approach for the near-real-time prediction

Users who have single-frequency receivers can use the new Klobuchar coefficients (α_{New} and β_{New}) to estimate the slant delays for the satellites that are visible to them. As pointed out in the introduction, because of the large temporal variation of the slant TEC (STEC) over the Indian region, using the single set of coefficients for a day may not provide sufficient accuracy over this region. Thus, a near-real-time prediction methodology which incorporates the actual variation of the TEC over the Indian region was worked out. Since the temporal variation of the ionosphere is not significant within a period of 5 min [3], it is assumed that the generated coefficients will remain valid up to the next 5 min. After every 5 min, the new set of coefficients will be broadcast. A flow chart of the methodology for the generation and prediction of the Klobuchar-like coefficients is illustrated in Fig. 1.

The illustration of the operational scheme that generates the new set of coefficients is given as follows:

1. Proposed methodology requires previous 24 h data, which is the total duration of the time window explained in Fig. 2, to generate the new set of coefficients. In this methodology, first, initialisation is done to estimate the delays using (4) and (5) from the original set of the Klobuchar coefficients broadcast

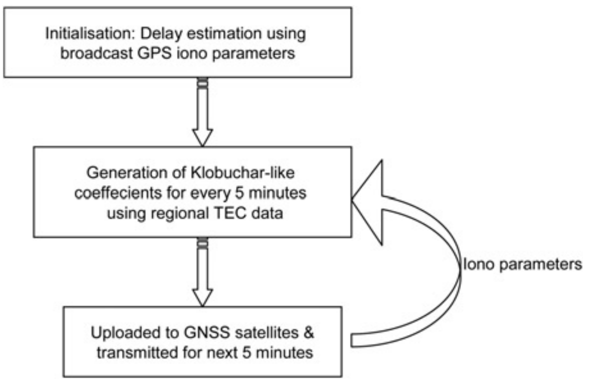


Fig. 1 *Flow chart of prediction methodology*

by the GPS satellites for that day. This is a one-time operation at the starting of the operation.
2. After initialisation, the Klobuchar-like coefficients are generated at time '*t*', that is, at the starting of the current day.
3. These coefficients will be broadcast by satellites through the uplink stations to predict the delay till the next '$t+5$' minutes.
4. To again generate a new set of the coefficients for the time '$t+5$', the time window will slide 5 min further from the previous day to append new 5 min data from the current day into the last 23 h and 55 min TEC data of the previous day, as illustrated in Fig. 2. This new 24 h TEC data will be used to generate the new set of coefficients taking the previously-generated set of coefficients as an initial guess using the steps (1–4).
5. Steps (1–5) are repeated to generate the new sets of coefficients for every next 5 min intervals.
6. The system will automatically update the coefficients at every 5 min using the newly generated set of the Klobuchar-like coefficients.

These coefficients will be generated in the Master Control Station in an optimised manner, as described in Section 2.1, using the TEC data collected in near-real-time from the 18 data collection stations. Generated coefficients will be formatted in the form of navigational messages and passed on to the uplink station for uplink to satellites. The satellites will broadcast these coefficients to the users. The users who have the single-frequency receivers will use the new coefficients to estimate the line of sight delays of the visible satellites using the Klobuchar algorithm for making the necessary corrections in the pseudo-range measurements. Fig. 3 shows the flow diagram of the overall methodology, from data collection to the coefficients generation and the pseudo-range corrections.

3 Data analysis

3.1 Data collection and pre-processing

For this analysis, the TEC data are collected from the 18 GPS stations in India as illustrated in Fig. 4. The NovAtel OEM4 dual-frequency GPS receivers at the $L1$ (1575.75 MHz) and $L2$ (1227.60 MHz) frequencies were used for this purpose. Collected data are recorded by data logger PCs at every 1 min interval. Recorded data are archived at the Space Applications Centre, Ahmedabad, after collecting it from all other TEC stations. Collected data are pre-processed at the archival station.

These dual-frequency receivers make measurements of the pseudo-range and the carrier phase data from all visible satellites above the cutoff elevation of 5° to calculate the TEC. It is assumed that the 5° elevation thresholds can effectively minimise the multi-path and other noise because of low elevation [13, 14]. The TEC obtained from the pseudo-range measurements is noisy, whereas the TEC from carrier phase is smooth but has integer ambiguity. Carrier smoothing is done to obtain noise free and absolute TEC by obtaining moving average of the difference between the TEC from code and carrier phase calculated at each epoch and adding to carrier phase TEC. The smoothed carrier phase TEC is fitted to the level of code TEC to obtain smoothed code TEC. These processes are done internally by the receivers to obtain the raw TEC data.

Before using the raw TEC data for the analysis, receiver bias has been removed by using the Kalman filter technique. As the daily variation of the receiver bias is very small, it is estimated once for 24 h and applied for that day. The satellite bias correction has also been applied. The satellite bias includes the differential $P_1 - P_2$ code bias and the differential $P_1 - C_1$ code bias, which can be estimated and measured separately. The differential $P_1 - P_2$ code bias can be determined from the GPS broadcast differential group delay (τ_{GD}) values by calculating the GPS offset time and mean τ_{GD} values. A method of estimating the $P_1 - P_2$ bias has been studied, and the working algorithm was developed. The $P_1 - C_1$ bias values are available on the CODE website (http://www.aiub.unibe.ch/ionosphere.html). These values were used and after converting into the TEC units, corrections were applied in the raw TEC data. After applying the satellite and receiver biases, the absolute true

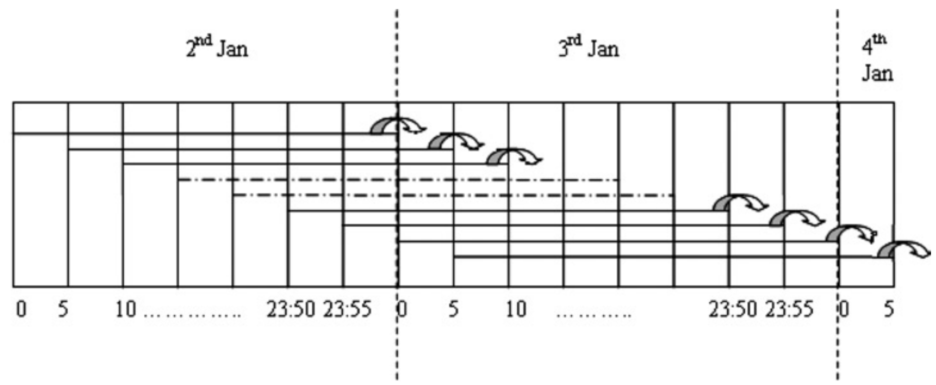


Fig. 2 *Illustration of the near-real-time prediction methodology*

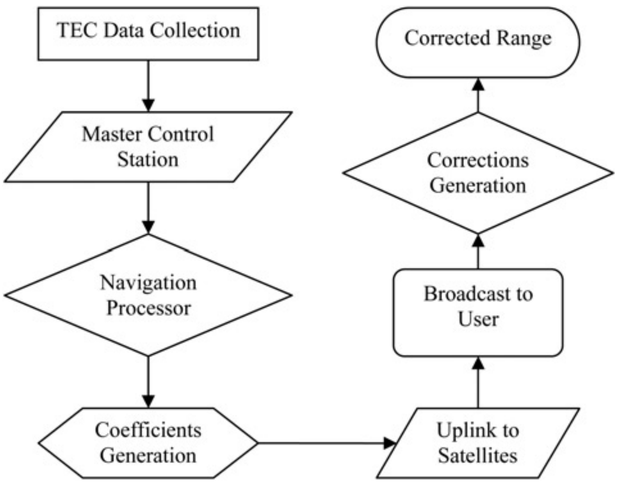


Fig. 3 *Overall flow diagram for implementation of the methodology*

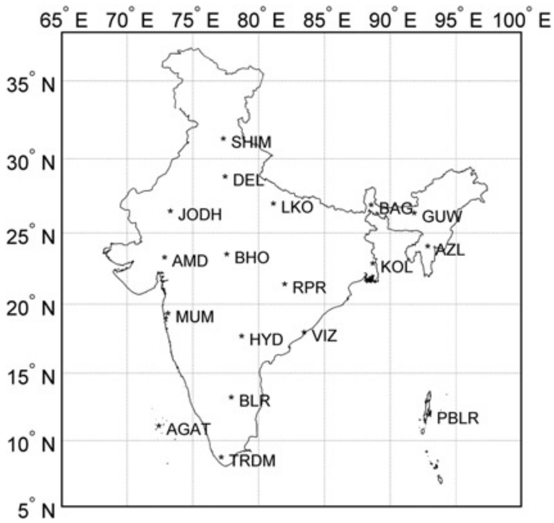


Fig. 4 *TEC data collection stations in India*

STEC is obtained. The detailed description of pre-processing of the TEC is provided by Shukla *et al.* [4, 5].

3.2 Testing methodology and validation

The new sets of coefficients were generated for the test stations without using the TEC data from those stations. For example, while generating the coefficients for the Bangalore test station (13.0N, 77.7E), the TEC data from all other 17 stations, except Bangalore station, is used. Since, the proposed prediction methodology is based on the assumption that generated coefficients at time '*t*' will remain valid till '*t* + 5' instance; therefore for the validation of the methodology, first, the delay is predicted for the next 5 min segment using the coefficients generated at the time '*t*'. Thereafter, error analysis is done using the predicted delays for '*t*'–'*t* + 5' min segment and the measured TEC of the same '*t*'–'*t* + 5' min segment. Further, in order to test the improvement and validate the accuracy of the new Klobuchar-like coefficients, figures of merit such as the total mean RMS (TRMS), the total mean correction percentage (TCP), and the daily mean error (DME) are presented [12]. The TRMS is the RMS value of the residual errors between the ionospheric delay estimates obtained from the dual-frequency GPS receivers and those obtained either by the original Klobuchar coefficients (Orig-Klob) or by the Klobuchar-like coefficients applying the proposed methodology (RT-Klob). For all the satellites observed at a station over all days, the corresponding $\mathrm{TRMS_s}$ of the above residual errors is given as follows:

$$\mathrm{TRMS_S} = \sqrt{\frac{\boldsymbol{V}^{\mathrm{T}}\boldsymbol{V}}{m_{\mathrm{s}} - 1}} \tag{6}$$

where

$$\boldsymbol{V}(i) = D_{\mathrm{Mes}}(i) - D_{\mathrm{est}}(i), \quad i = 1, 2, 3, \ldots, m_{\mathrm{s}}$$

Here, m_{s} is the total number of observations received at the station '*s*' over the days considered for the analysis, D_{Mes} is the actual measured delay using the dual-frequency GPS receivers and D_{est} is the ionospheric delay estimated from each respective set of the newly generated Klobuchar-like coefficients or from the actually broadcast ones. Superscript 'T' denotes the transpose of the matrix '$\boldsymbol{V}$'. The TRMS of the above residual errors corresponding to all the visible satellites from all the stations over all days is given as

$$\mathrm{TRMS} = \sum_{1}^{n_{\mathrm{s}}} \mathrm{TRMS_s}/n_{\mathrm{s}} \tag{7}$$

where n_{s} is the number of stations considered for testing on all days.

$\mathrm{TCP_s}$ is the correction percentage of the ionospheric delays calculated using the different sets of the Klobuchar coefficients with respect to the actually measured delay D_{a} from the dual-frequency receivers for all the satellites observed at station '*s*' over all days [12].

$$\mathrm{TCP_s} = \left(1 - \frac{\sum_{i=1}^{n}\left((|D_{\mathrm{a}}(i) - D_{\mathrm{m}}(i)|)/(D_{\mathrm{a}}(i))\right)}{m_{\mathrm{s}}}\right) \times 100\% \tag{8}$$

The TCP of the above ionospheric delays corresponding to all satellites at all stations over all days is given as follows

$$\mathrm{TCP} = \sum_{i=1}^{n_{\mathrm{s}}} \mathrm{TRMS}_{\mathrm{s}_i}/n_{\mathrm{s}} \tag{9}$$

The validation was done by obtaining the absolute GPS position using the International GNSS Station (IGS) data including *P*1 (pseudo-range at *L*1) and *P*2 (pseudo-range at *L*2) frequencies. The following equation is used to calculate the position error as [12, 15, 16]

$$dr = \sqrt{(X_a - X_b)^2 + (Y_a - Y_b)^2 + (Z_a - Z_b)^2} \tag{10}$$

where (X_a, Y_a, Z_a) are very accurately known coordinates of the test stations and (X_b, Y_b, Z_b) are the computed coordinates of the test stations. The mean of the positions over the day for a test station is defined as the DME and is expressed by the following equation

$$\mathrm{DME} = \sum_{i=1}^{n} dr_i/n \tag{11}$$

doi: 10.1049/iet-rsn.2011.0371

where 'n' is the total number of observations for which position is calculated.

4 Results and discussion

The Klobuchar-like coefficients are generated every 5 min by the methodology described in Section 2.2 using the TEC data collected from the 18 dual-frequency GPS receivers in India. The new set of coefficients for the test stations were generated without using the TEC of that station. The performance of the prediction of the delay using the generated coefficients was tested for the geomagnetic quiet days of 2005. For this analysis, the A_p index less than 50 is considered as quiet days, which covers days with geomagnetic activity up to the minor storms and excludes the major and severe storms and the A_p index greater than 300 is considered as severely disturb days [17]. The A_p index is a measure of the general level of geomagnetic activity over the globe for a given day. It is derived from the measurements made at a number of stations world-wide of the variation of the geomagnetic field because of the currents flowing in the earth's ionosphere and, to a lesser extent, in the earth's magnetosphere.

For providing a clearer view of the improvement obtained from the new Klobuchar coefficients, generation of the coefficients was done for every 5 min segment, that is, t, $t+5$, $t+10, \ldots, t+23{:}50$ min with validity till $t+5$, $t+10$, $t+15, \ldots, t+23{:}55$ min, respectively. Generation of 288 such 5 min segments was done to obtain the delays for the whole day. Process was continued for next four consecutive days from 25 to 28 January 2005. In Fig. 5, the TRMS in the STEC (in TECU) is plotted in the vertical axis with time in UT in horizontal axis for Shimla (31.1N, 77.1E) for 25–28 January 2005. Dotted line shows the TRMS between the measured TEC and the TEC using the new Klobuchar-like coefficients, whereas solid line shows the TRMS between the measured TEC and the TEC using the Klobuchar coefficients broadcast by the GPS satellites.

In this regard, from Fig. 5 it can be observed that the TRMS in the STEC (in TECU) for a test station Shimla (31.1N, 77.1E). The TRMS is obtained using (8) with m_s in denominator as the total number of observations from all the visible satellites at that particular time. The TRMS is shown by vertical axis, whereas horizontal axis represents time in UT. Dotted line shows the TRMS between the measured TEC and the TEC obtained using the new Klobuchar-like coefficients, whereas solid line shows the TRMS between the measured TEC and the TEC obtained using the Klobuchar coefficients broadcast by the GPS satellites. From the figure, it can be observed that using the new Klobuchar-like coefficients, the TRMS in the STEC is significantly low in comparison with the original Klobuchar coefficients. It is to be noted that the new Klobuchar-like coefficients are updated every 5 min, whereas the original Klobuchar coefficients are updated only once (minimum update interval) in a day.

A more detailed analysis of the correction effectiveness is given in Table 1 by means of the statistical types TRMS (m) and TCP (%) for six more GPS test stations, including Shimla, for the geomagnetic quiet days from 25 to 28 January 2005. The test stations and their locations (in latitude and longitude) are provided in Table 1. These stations are arranged in the decreasing order of the latitude from top to bottom as given in Table 1. It can be observed from the table that the proposed methodology with the newly generated Klobuchar coefficients (RT-Klob) show good improvement over the actually broadcast Klobuchar coefficients (Orig-Klob) for almost all stations considered. It can further be observed that, in general, the improvement is significant for the stations, which lie near to the equatorial anomaly, such as Ahmedabad, Bhopal and Delhi. Other stations such as Shimla, which lie above anomaly belt, also show considerable improvement. Similar results are shown for another time from 11 to 14 September 2005 in 5th and 6th column of Table 1.

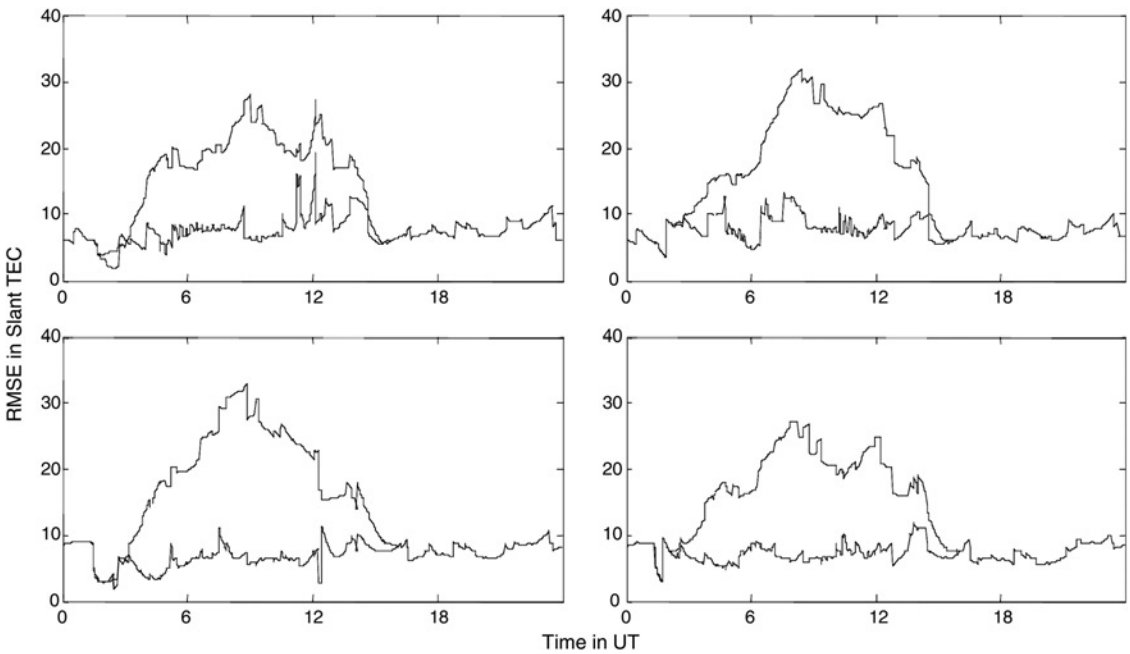


Fig. 5 *TRMS in the STEC (in TECU) for Shimla (31.1 N, 77.1 E) for 25–28 January 2005*

Dotted line shows the TRMS between the measured TEC and the TEC using the new Klobuchar-like coefficients, whereas the solid line shows the TRMS between the measured TEC and the TEC using the Klobuchar coefficients broadcast by the GPS satellites

Table 1 Comparison of the ionospheric delays using the GPS broadcast (Orig-Klob) and the new Klobuchar-like coefficients (RT-Klob) with the measured delays for 25–28 January and 11–14 September 2005

Coefficient type					
		25–28 January 2005		11–14 September 2005	
GPS stations	Statistical types	Orig-Klob	RT-Klob	Orig-Klob	RT-Klob
Shimla	TRMS, m	2.7230	1.2644	2.9470	2.4577
(31.1N, 77.1E)	TCP, %	64.80	82.16	89.23	90.31
Delhi	TRMS, m	2.5308	1.4199	2.5846	1.8384
(28.6N, 77.2E)	TCP, %	79.29	89.29	95.73	96.55
Jodhpur	TRMS, m	2.4374	1.6883	3.8351	2.2066
(26.3, 73.1E)	TCP, %	82.43	87.54	83.44	83.82
Bhopal	TRMS, m	2.3376	1.8998	3.6985	2.2096
(23.3 N, 77.3E)	TCP, %	86.67	88.94	94.79	96.53
Ahmedabad	TRMS, m	4.1284	2.5237	4.7835	2.9444
(23.1N, 72.6E)	TCP, %	61.37	85.23	51.55	77.65
Hyderabad	TRMS, m	1.8409	1.7755	4.2461	2.0014
(17.5N, 78.5E)	TCP, %	82.96	83.03	88.93	91.30
Bangalore	TRMS, m	1.5339	1.4993	3.4569	1.9808
(13.0N, 77.7E)	TCP, %	92.16	92.68	86.25	87.92
total mean	TRMS, m	2.5046	1.7244	3.6502	2.2341
	TCP, %	78.53	86.98	84.27	89.15

To further validate the results shown in Table 1, absolute positioning is performed using the software developed by Shukla *et al.* [18] for single-point positioning. In this software, all possible corrections, such as the clock, the ephemeris, the propagation delays and the transit time are applied. Using this software, position of the IGS test station IISc-Bangalore was calculated for an arbitrarily chosen period of the four consecutive geomagnetic quiet days from 24 to 27 May 2005 with A_p index < 50 and a period of four consecutive disturbed days from 11 to 14 September 2005 with A_p index >300. The IISc-Bangalore station was chosen because of the availability of very accurate and continuous observation and navigation data collected by the IGS receiver. The DME of position error is calculated for IISc-Bangalore as a test station with respect to the accurately known position of the station.

Fig. 6 shows the DME in absolute positioning for four consecutive quiet days from 24 to 27 May 2005. It can be observed from the Fig. 6 that the DME in position for all days is minimised by using Klobuchar-like coefficients (RT-Klob). The improvement is mainly because of the combined effect of the fine tuning of the actually broadcast Klobuchar coefficients for the Indian region using the regional TEC data and the novel approach for prediction of the delay.

The improvement in the DME because of the new prediction methodology can further be validated by Figs. 7 and 8, in which the DME is shown, respectively, for four consecutive days from 11 to 14 September 2005 and 27 to 30 April 2007. It can be observed from the Figs. 7 and 8 that the maximum improvement in the DME over originally broadcast Klobuchar coefficients because of the new prediction methodology is 1.74 and 3.97 m, respectively. The reason behind this improvement is that, the new methodology is able to capture short-term variations in the TEC. This indicates that the newly generated Klobuchar-like coefficients are more adaptive and are able to capture the variation in actual TEC, which in turn improves the prediction accuracy.

Since, India lies in the EIA region, large temporal variations in TEC are observed in this region. To incorporate these variations, the generation of new Klobuchar coefficients every 5 min may be of great importance. This is because the new coefficients are generated using the recently

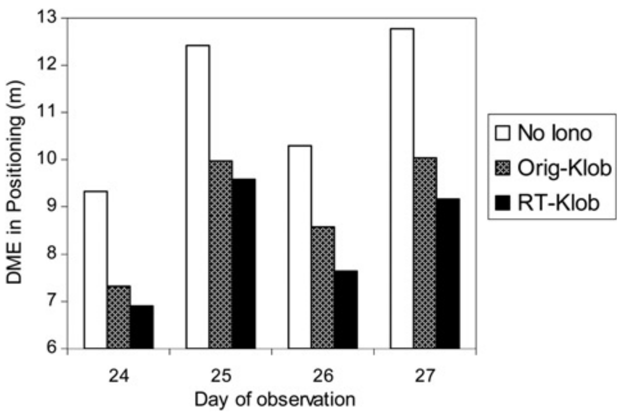


Fig. 6 *External error of positioning of IISc-Bangalore for four consecutive quiet days from 24 to 27 May 2005 with no ionospheric correction (No Iono, white bar)*

Original broadcast Klobuchar coefficients (Orig-Klob, middle bar) and real-time Klobuchar coefficients (RT-Klob, black bar)

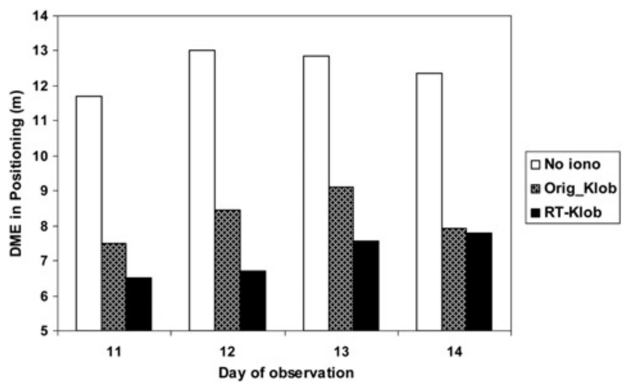


Fig. 7 *External error of positioning of IISc-Bangalore for four consecutive severely disturb days from 11 to 14 September 2005 with no ionospheric correction (No Iono, white bar)*

Original broadcast Klobuchar coefficients (Orig-Klob, middle bar) and real-time Klobuchar coefficients (RT-Klob, black bar)

doi: 10.1049/iet-rsn.2011.0371

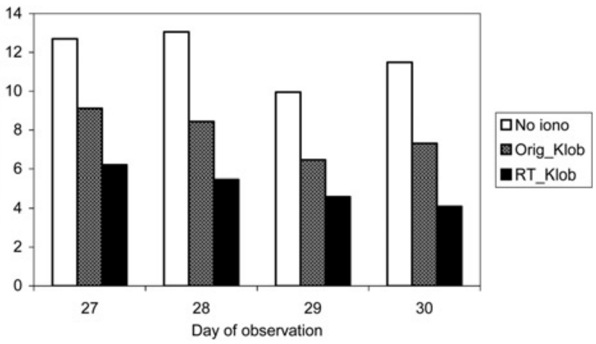


Fig. 8 *The external error of positioning of IISc-Bangalore for four consecutive severely disturb days from 27 to 30 April 2007 with no ionospheric correction (No Iono, white bar)*

Original broadcast Klobuchar coefficients (Orig-Klob, middle bar) and real-time Klobuchar coefficients (RT-Klob, black bar)

acquired TEC data, which automatically capture the short-term variations in the TEC and can be used for the near-real-time prediction of the delay and will provide better accuracy than the original Klobuchar coefficients as demonstrated by Figs. 6 and 7.

An examination of the shorter update interval of 2 min is also done for all the test stations to understand the sensitivity of the assumption that the TEC remains constant over 5 min. It is found that, using the new Klobuchar-like coefficients which are valid for 2 min, the maximum change in the TRMS is only 0.04 m (for the test station Shimla (31.1N, 77.1N)). Therefore it is not useful to update the coefficients for the shorter rate than 5 min. This will also increase the system load without providing much improvement in the accuracy.

Furthermore, unlike the GPS constellation, the proposed IRNSS constellation consists of Geostationary Earth Orbit (GEO) and Geo Synchronous Orbit (GSO) satellites which will be visible to the user most of the times, hence updating is possible in short-time intervals.

5 Conclusions

The applicability of ionospheric corrections using the Klobuchar model for single-frequency GPS users over the Indian region is limited because of the presence of complex ionospheric structures with EIA. The Klobuchar coefficients broadcast by GPS satellites do not incorporate short-term variations of TEC. This limits the use of the Klobuchar coefficients in near-real-time mode. In this paper, generation of Klobuchar-like coefficients, especially for the EIA region, is demonstrated. These coefficients are optimised over the Indian region using regional TEC data from existing network in India.

Further, to accommodate the short-term temporal variability of the ionosphere, a novel prediction methodology was developed. The methodology proposes to broadcast set of the new coefficients every 5 min generated by using the TEC data of the previous 24 h. A very important feature of this methodology is that it adapts and the prediction time can be varied according to the user requirement and the system budget. The performance of the model was evaluated using the TEC data collected from the 18 stations in India. The validation is also done in absolute point positioning mode for IISc-Bangalore, India, as a test station. Prediction with the newly generated coefficients improved the delay estimation significantly in comparison to the Klobuchar coefficients broadcast by the GPS satellites. The proposed methodology is very useful for more accurate prediction of the delay for the single-frequency users of the regional satellite systems such as the proposed IRNSS for the Indian region.

The proposed method will require only 64 bits (8×8) to transmit the eight Klobuchar coefficients (8 bits are required to transmit any one of the α or β parameters). Total 288 such sets of the real-time Klobuchar coefficients will be required to be uplinked in 1 day (24 h). Thus, with the proposed methodology, structure of the original Klobuchar algorithm will remain the same, only the system load will increase with the requirement of updating the coefficients every 5 min.

Furthermore, the proposed methodology provides better accuracy without changing the structure of the original Klobuchar algorithm. Fitting of the amplitude with a higher-order polynomial (degree >3) may also be another option, which will be explored by the authors in the future work. However, this option will increase the computational complexity in user receivers.

6 Acknowledgments

The authors express their sincere thanks to the Scientists/Engineers from AAI and ISRO, who helped in establishment of the 18 GPS Stations and the TEC data collection, for carrying out this study. The authors are also thankful to the International GNSS Service (IGS) for providing the data products to the research community.

7 References

1 Misra, P., Enge, P.: ‘Global positioning system: signals, measurements and performance’ (G-J Press, Massachusetts, 2001), Ch.1, pp. 137–140
2 Lanyi, G.E., Roth, T.: ‘A comparison of mapped and measured total ionospheric electron content using global positioning systems and beacon satellite observations’, *Radio Sci.*, 1988, **23**, (4), pp. 483–492
3 RTCA special committee 159: ‘Minimum operational performance standards for airborne equipment using global positioning system/wide area augmented system’. RTCA/DO – 229 C, November 2001
4 Shukla, A.K., Nagori, N., Das, S., Jain, N., Sivaraman, M.R., Bandyopadhyay, K.: ‘Statistical comparison of various interpolation algorithms for grid-based single shell ionospheric model over Indian region’, *J. Global Positioning Syst.*, 2008, **7**, (1), pp. 72–79
5 Shukla, A.K., Das, S., Nagori, N., Sivaraman, M.R., Bandyopadhyay, K.: ‘Two-shell ionospheric model for Indian region: a novel approach’, *IEEE Trans. Geosci. Remote Sens.*, 2009, **47**, (8), pp. 2407–2412
6 Klobuchar, J.A.: ‘Ionospheric time delay algorithm for single frequency GPS users’, *IEEE Trans. Aerosp. Electron. Syst.*, 1987, **23**, (3), pp. 325–331
7 Feess, W.A., Stephens, S.G.: ‘Evaluation of GPS ionospheric time-delay model’, *IEEE Trans. Aerosp. Electron. Syst.*, 1987, **23**, (3), pp. 332–338
8 Sarma, A.D., Madhu, T., Sarma, N.S.M.: ‘An ionospheric time delay model based on IRI-90 for space-bound objects within 300 km altitude’, *Indian J. Radio Space Phys.*, 2003, **32**, pp. 148–153
9 Rama Rao, P.V.S., Jayachandran, P.T., Sri Ram, P.: ‘Ionospheric irregularities: the role of the equatorial ionization anomaly’, *Radio Sci.*, 1997, **32**, (4), pp. 1551–1557
10 Bhuyan, P.K., Borah, R.R.: ‘TEC derived from GPS network in India and comparison with the IRI’, *Adv. Space Res.*, 2007, **35**, (9), pp. 830–840
11 Yuan, Y., Ou, J.K.: ‘An improvement on ionospheric delay correction for single-frequency GPS users – the APR I scheme’, *J. Geod.*, 2001, **75**, (5/6), pp. 331–336
12 Yuan, Y., Huo, X., Ou, J., *et al*: ‘Refining the Klobuchar ionospheric coefficients based on GPS observations’, *IEEE Trans. Aerosp. Electron. Syst.*, 2008, **44**, (4), pp. 1498–1510

13 Rost, C., Wanninger, L.: 'Carrier phase multipath corrections based on GNSS signal quality measurements to improve CORS observations'. Proc. IEEE/ION PLANS, CA, May 2010, pp. 3–6
14 Van Bree, R.J.P., Buist, P.J., Tiberius, C.C.J.M., Arem, B.V., Knoop, V.L.: 'Lane identification with real time single frequency precise point positioning: a kinematic trial'. Proc. ION GNSS, Portland, Oregon, September 2011, pp. 19–23
15 Yuan, Y., Tscherning, C.C., Knudsen, P., Xu, G., Ou, J.: 'The ionospheric eclipse factor method (IEFM) and its application to determining the ionospheric delay for GPS', *J. Geod.*, 2008, **82**, (1), pp. 1–8
16 Yuan, Y., Huo, X., Ou, J.: 'Models and methods for precise determination of ionospheric delay using GPS', *Prog. Nat. Sci.*, 2007, **17**, (2), pp. 187–196
17 El-Arini, M.B., Walter, P., Roland, L., Robert, C., James, F., Kelly, M.: 'An introduction to wide area augmentation system and its predicted performance', *Radio Sci.*, 2001, **36**, (5), pp. 1233–1240
18 Shukla, A.K., Shinghal, P., Sivaraman, M.R., Bandyopadhyay, K.: 'Comparative analysis of the effect of ionospheric delay on user position accuracy using single and dual frequency GPS receivers over Indian region', *Indian J. Radio Space Phys.*, 2009, **38**, pp. 57–61

doi: 10.1049/iet-rsn.2011.0371