A THREE-DIMENSIONAL APPROACH TO IMPROVE THE INTERNATIONAL REFERENCE IONOSPHERE (IRI) MODEL

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ABSTRACT:

A three-dimensional model based on time and location is introduced to enhance the accuracy of vertical total electron content (VTEC) global ionosphere maps (GIMs) of ionosphere empirical models. The chosen empirical model is the International Reference Ionosphere 2016 (IRI-2016) model and observations are the GIMs VTEC values from Center for Orbit Determination in Europe (CODE). For this purpose, IRI-2016 is considered as a background model and the VTECs from GIMs are considered as the correction term. The correction term is modelled using spherical harmonics expansion base functions with a degree equal to 15 in Earth-fixed coordinate system with a polynomial B-spline base function for time resolution. The improved VTEC maps are constructed on 1st January 2018 with a Kp index of 4. The root mean square error (RMSE) improvements range from 1.65 TECU to 2.81TECU about 70 percent to 85 percent and the bias improvements are from 0.28 TECU to 1.00 TECU with an average of 0.75 TECU, respectively.

1. INTRODUCTION

The applications that rely on radio communication and observation data from the global navigation satellite system (GNSS) are influenced by ionosphere layer. There are global and local ionospheric parameters models based on mathematical, empirical and physical approaches. Vertical total electron content (VTEC) is recognized as a very important ionosphere parameter indeed. With the incensement in ionospheric data, many ionospheric models have been established (Dudeney, 1978, Brunini, et al., 2004). Physical models utilize the physical equations and quantities, for instance, the global assimilation of ionospheric measurements (GAIM) (Wang, et al., 2004, Schunk, et al., 2004). In mathematical modelling, space-based observations are used to model ionospheric parameters. For example, the reliable daily global ionosphere maps (GIM) have been produced from International GNSS Service (IGS) (Schaer, 1999). Empirical models, including the International Ionosphere Reference Model (IRI), use a large number of parameters of existing data sets from terrestrial and satellite systems and solar radiation to model the ionosphere (Bilitza, 2001, Bilitza, et al., 2011).
Among empirical ionospheric models, IRI model is one of the most significant one to evaluate ionosphere characteristics and parameters. However, numerous studies have evaluated the prediction of ionosphere total electron content (TEC) by IRI and the results show that most of the globally TEC anticipated by IRI model vary significantly from observational data in different areas, specially at the equatorial ionospheric anomaly (EIA) regions (Adeniyi, et al., 2003, Batista and Abdu, 2004, Bhuyan and Borah, 2007, Zhang, et al., 2007, Chuo and Lee, 2008, Wichaipanich, et al., 2010, Maltseva, et al., 2012, Wichaipanich, et al., 2012, Olwendo, et al., 2013, Kumar, et al., 2015).
In many studies, the space geodetic observations such as radio occultation, altimetry satellites and low earth orbit satellites (LEO) data are used for the purpose of the improvement of VTEC maps from IRI model (Dettmering, et al., 2011, Liang, et al., 2015, Karimi, et al., 2022).
Ionospheric parameters can be modelled using spherical harmonics and B-spline mathematical base functions (Ping, et al., 2002, Schmidt, 2007, Zeilhofer, 2008, Limberger, 2015, Erdogan, et al., 2017). On the basis of latitude and longitude, VTEC is often represented globally in two dimensions utilizing a spherical harmonics expansion as a base functions with a certain resolution (i.e., usually degree equal to 15) for defined time spans in a sun-fixed frame (Dettmering, 2003).
In this paper, the improvement of the VTEC maps of IRI-2016 model is achieved based on the IGS GIMs of the Center of Orbit Determination in Berne (CODE) in three dimensions considering time parameter. The model has a one-hour temporal resolution and for the spatial part, the resolution along the latitude is 2.5° and along the longitude is 5°, respectively (Hernández-Pajares, et al., 2009). We introduce a global VTEC map as an improved IRI-2016 model, that is on the basis of the polynomial B-spline base functions for time component and spherical harmonics functions for the latitude and longitude components in an Earth-fixed frame. The VTEC predictions on 1st January 2018 with Kp index of about 4 are calculated globally and then compared to the VTEC maps of the IGS produced by CODE.
The determination of VTEC parameter values from IRI and IGS maps is presented in section 2 of the text that follows. the modelling approach is discussed in section 3, and section 4 provides the results of paper. At last, section 5 gives the study's conclusion.

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2. DATA

in this study, VTECs of the VTEC maps from IRI-2016 empirical Model and IGS are used as datasets, which are explained below.

2.1 IRI

In order to create an international standard model for determining plasma parameters in the Earth ionosphere, the International Union of Radio Sciences and Committee on Space Researches (URSI / COSPAR) developed the project of IRI Model in the 1960s. This model presents the average monthly temperature and density of the electron, temperature and structure of ion at 60 km to 2000 km altitude and is depending on observations from the global ionosounds network, the incoherent scatter radars, and instrumentation on several rockets and satellites (Bilitza, et al., 2011, Bilitza, et al., 2014). In this study, IRI-2016 VTEC global maps are used, which have the same resolution as IGS VTEC maps in ionosphere exchange (IONEX) format (Bilitza, et al., 2017).

2.2 IGS

IGS has four ionosphere associate analysis centers (Li, et al., 2018). The centers have regularly provided valid daily global ionospheric maps in the format of IONEX since the IGS working group was established in 1998 (Roma-Dollase, et al., 2018). According to (Hernández-Pajares, et al., 2009), the spatial resolution of the IONEX format is 5 degrees in line with longitude and 2.5 degrees in line with latitude. The accuracy of the IRI-2016 VTEC maps has been enhanced in this study using the IGS VTEC data provided by CODE.

3. METHOD

The spherical harmonics expansion can represent the function $f(x) = f(\varphi, \lambda)$ with the geodetic latitude (φ) and longitude (λ) in the Earth-fixed reference frame given on the surface of a sphere at time of p (t_p) as follows (Schmidt, et al., 2007):

$$\begin{aligned} f(\varphi,\lambda,t_p) &= \\ &\sum_{n=0}^{N}\sum_{m=0}^{n}\tilde{P}_{nm}(\sin\varphi)\left(\bar{C}_{n,m}(t_p)\cos(m\lambda)+\bar{S}_{n,m}(t_p)\sin(m\lambda)\right) \\ &= \sum_{n=0}^{N}\sum_{m=0}^{n} h_{n,m}(t_p) Y_{n,m}(\varphi,\lambda) \end{aligned} \tag{1}$$

where $\tilde{P}_{nm}(\sin\varphi)$ = associated normalized Legendre function
n = degree
m = order

For each signal value (i.e., $f(\varphi_r, \lambda_r)$, with r = 1,.., R) it can be assumed that $f(\varphi_r, \lambda_r, t_p) = f_r(t_p)$, which can be written in a scalar form:

$$f_r(t_p) = a_r^T h_p \tag{2}$$

Considering the IRI as a background model, modelling is performed based on the differences between the VTEC values obtained from CODE and VTECs derived from IRI model, i.e.:

$$\begin{aligned} f(\varphi,\lambda,t) &= \Delta VTEC(\varphi,\lambda,t) = \\ &VTEC(\varphi,\lambda,t) - VTEC_{ref}(\varphi,\lambda,t) \end{aligned} \tag{3}$$

where $VTEC(\varphi,\lambda,t)$ = VTEC from GIMs from CODE
$VTEC_{ref}(\varphi,\lambda,t)$ = VTEC from IRI model

It can be assumed that $\Delta VTEC$ values are given as:

$$f(\varphi_r, \lambda_r, t_p) = f_r(t_p) = l_r(t_p) + e_r(t_p) \tag{4}$$

where $l_r(t_p)$ = $\Delta VTEC$ observation
$e_r(t_p)$ = measurement errors

Equation 5, can be derived by rewriting Equation 2 as the linear equation system for all observations at all times (i.e., r = 1, …, R and p = 1, …, P on the sphere):

$$l_p + e_p = A h_p \tag{5}$$

with

$$A = [a_1, a_2, ..., a_R] \tag{6}$$

Furthermore, the unknown series coefficients for the time dependency can be obtained according to the following equations using polynomial B-spline functions with level *J* and shift *K*:

$$H_{n,m}(t_p) = \sum_{k=0}^{K_J-1} h_{n,m,k}^J \phi_{J,k}(t_p) \tag{7}$$

where $\phi_{J,k}$ = base functions
$h_{n,m,k}^J$ = unknown series coefficients

Equation 7 can be written in the form of Equation 8 for series coefficients (i.e., m and n), therefore:

$$H_p = H q_p \tag{8}$$

with

$$H = \begin{bmatrix} h_{0,0,0}^J & h_{0,0,1}^J & \cdots & h_{0,0,K_J-1}^J \\ h_{1,-1,0}^J & h_{1,-1,1}^J & \cdots & h_{1,-1,K_J-1}^J \\ \vdots & \vdots & \ddots & \vdots \\ h_{N,N,0}^J & h_{N,N,1}^J & \cdots & h_{N,N,K_J-1}^J \end{bmatrix} \tag{9}$$

$$q_p = \left[\phi_{J,0}(t_p), \phi_{J,1}(t_p), ..., \phi_{J,K_J-1}(t_p)\right]^T \tag{10}$$

By defining the matrix $Q = [q_1, q_2, ..., q_P]$ for the observations in hours *t = 1, …, P*, the Equation 11 can be achieved as:

$$L + E = AHQ \tag{11}$$

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By estimating the unknown coefficients (matrix *H*) using the Least-Squares adjustment, the VTEC can be obtained at any location and time (Schmidt, 2007, Schmidt, et al., 2011).

It should be noted that for evaluating the accuracy of the modelling, the VTEC maps from IGS are considered as valid maps. Also, The root mean square error (RMSE) value and bias value can be introduced as (Shi, et al., 2019) :

$$RMSE = \sqrt{\frac{\sum_{r=1}^{R}\left(VTEC_{maps}^{r} - VTEC_{IGS}^{r}\right)^2}{R}} \tag{12}$$

$$bias = \frac{1}{R}\sum_{r=1}^{R}\left(VTEC_{maps}^{r} - VTEC_{IGS}^{r}\right) \tag{13}$$

where $VTEC_{IGS}^{r}$ = final VTEC maps from IGS
$VTEC_{maps}^{r}$ = constructed VTEC maps
R = number of observations

4. RESULTS

In this research, three-dimensional modelling of the VTEC is achieved by choosing the degree (N in Equation 1) equal to 15 for the spatial resolution and the level equal to 3 (J in Equation 7) for the time resolution. We randomly chose 3000 observations of the IONEX regular grid from IGS VTEC maps and IRI-2016 VTEC maps at the same location and time (i.e., R=3000 and P=24 in Equation 4) on 1st January 2018. The global VTEC maps (VTEC-Maps) are obtained with one-hour temporal resolution in the IONEX format (i.e., 24 VTEC-Maps in IONEX regular grid points for each hour of the universal time (UT)). The produced VTEC-Maps at different periods on 1st January 2018 are demonstrated in Figure 1 to Figure 4 with the periods of 4 UT, 10 UT, 16 UT, and 22 UT, respectively.

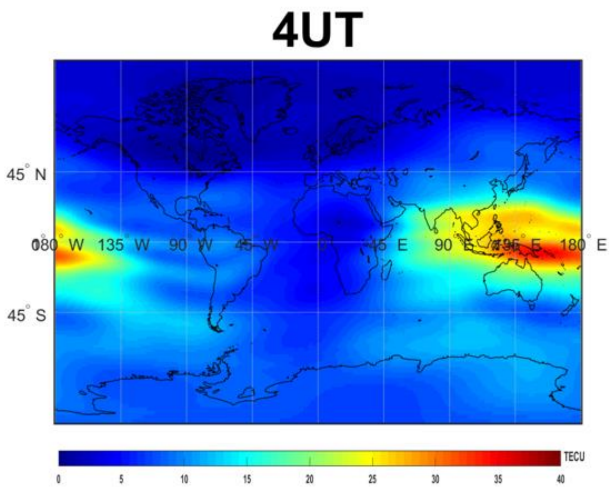

Figure 1. VTEC-Map at UT = 4 on 1st January 2018.

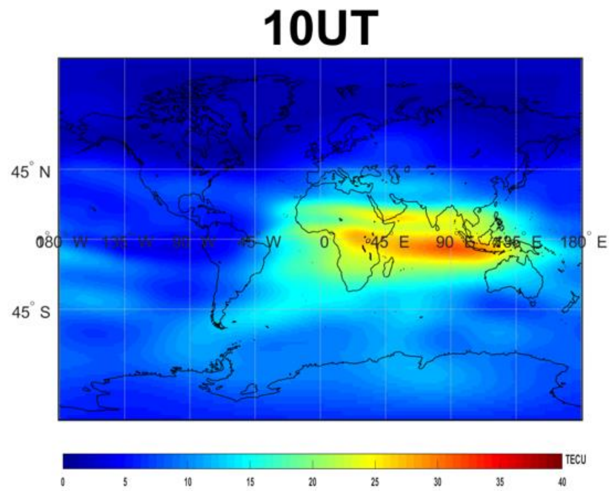

Figure 2. VTEC-Map at UT = 10 on 1st January 2018.

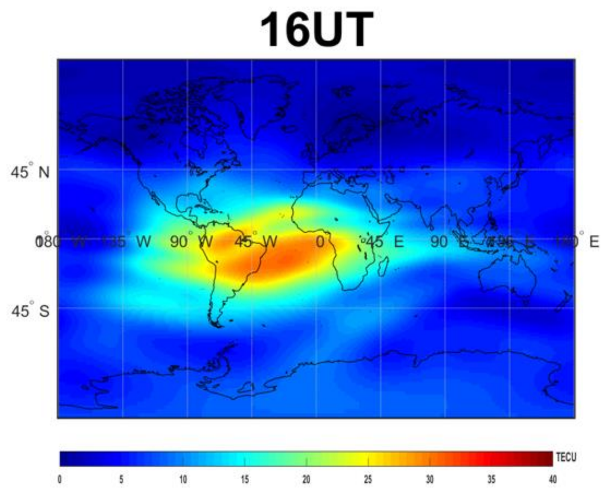

Figure 3. VTEC-Map at UT = 16 on 1st January 2018.

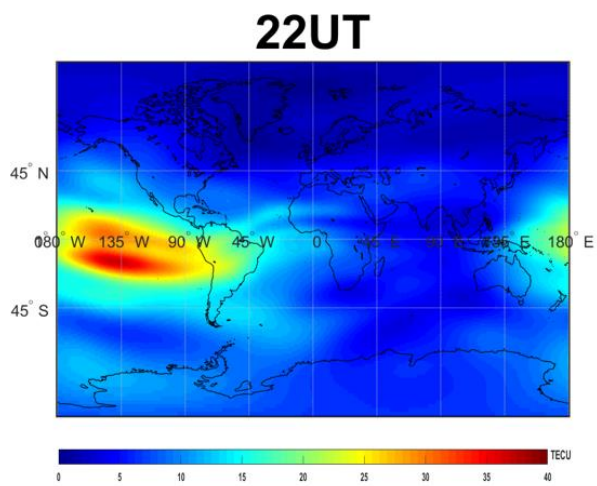

Figure 4. VTEC-Map at UT = 22 on 1st January 2018.

The Kp index of 1st January 2018 is close to 4. Kp indices characterize the geomagnetic storms' magnitude and are described on the eight three hourly time span of the universal time day from 00 UT to 24 UT (Matzka, et al., 2021a, Matzka, et al., 2021b). Figure 5 depicts the three-hourly Kp indices on the selected day for modelling.

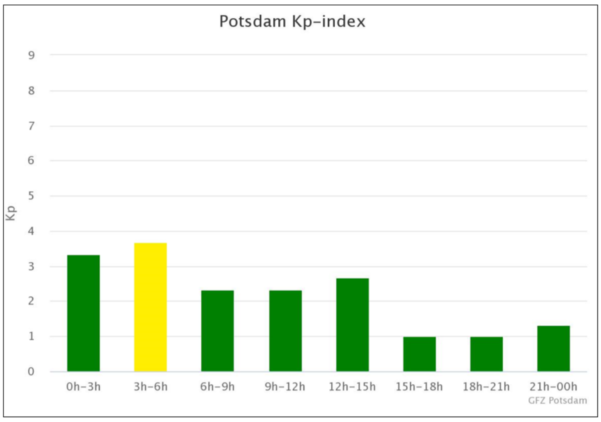

Figure 5. Official Kp indices on 1st January 2018.

Figure 6 illustrates the time series of RMSE values for VTEC-Maps and IRI-2016 VTEC maps on 1st January 2018. The RMSE values of produced VTEC-Maps compared to the RMSE values of IRI-2016 VTEC maps have been reduced in the range of [1.65, 2.81] TECU equal to 70-85 percent and totally the RMSE values reduced with an average of 1.93 TECU during the selected day.

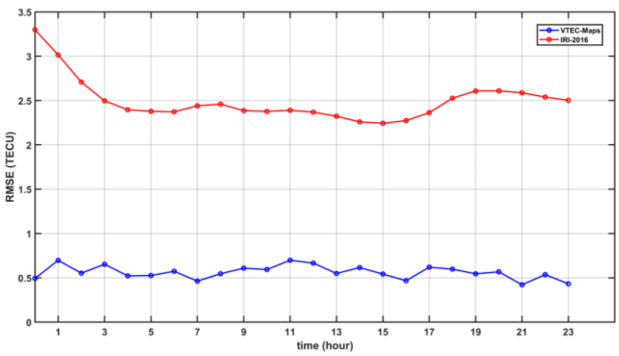

Figure 6. The time series of RMSE values.

The time series of bias values for VTEC-Maps and IRI-2016 VTEC maps on 1st January 2018 is shown in Figure 7. In this Figure, bias values of the produced VTEC maps and IRI-2016 VTEC estimates are in the range of [-0.05, 0.04] and [-1.03, -0.30] TECU, respectively. The average decrease of the Bias was about 0.75 TECU during the day.

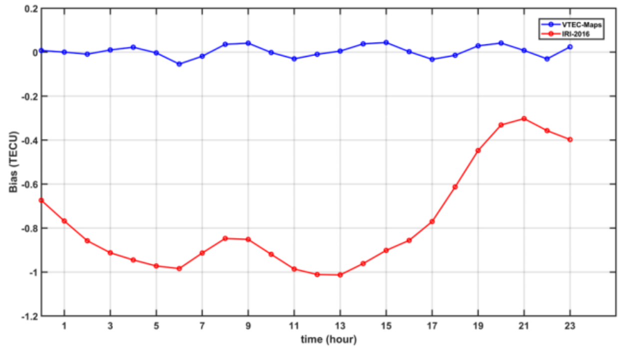

Figure 7. The time series of bias values.

The reduction in RMSE and bias values of produced VTEC-Maps in comparison with the IRI-2016 model illustrates the improvement in the accuracy of the VTEC maps of IRI-2016 by implementing the introduced approach.

5. CONCLUSIONS

In this study, VTEC data from IGS VTEC maps from CODE are utilized to enhance the accuracy of IRI-2016 VTEC maps on a day with a Kp index of about 4. The IRI-2016 model is considered as a background model and The differences of 3000 random VTECs observations from IGS maps and IRI-2016 at the same position and time are considered as input data. For three-dimensional modelling of the VTEC the spatial part is represented using spherical harmonics functions and the time part is represented by polynomial B-spline functions. Next, unknown coefficients of three-dimensional model are estimated through Least Squares adjustment. The RMSE values of produced VTEC-Maps compared to the RMSE values from IRI-2016 VTEC maps decreased by an average of 1.93 TECU equivalent to 77 percent. Moreover, the bias values declined by [0.29, 1.00] TECU with an average of 0.75 TECU on 1st January 2018. The results indicate the effectiveness of the introduced three-dimensional procedure, which improved the accuracy of the VTEC values of IRI-2016 model.

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