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Performance Evaluation of Two Interpolation Techniques for GPS/BeiDou-Based Regional TEC Model

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SUMMARY

This study aims to develop a regional ionospheric model (RIM) based on the combined GPS/BeiDou observations over Europe. GPS/BeiDou observations from 16 reference stations are processed in the zero-difference mode. The bi-linear expansion function is used to model the vertical total electron content (VTEC). Then, a least-squares algorithm is developed to determine the TEC parameters for a 15-minute time interval. In order to estimate the VTEC values at a 1º×1º grid, two different interpolation methods are used, including the inverse distance weighted (IDW) and the Kriging methods. To assess the accuracy of the developed model using those two methods, the VTEC values are estimated and compared with the international GNSS service global ionospheric maps (IGS-GIMs) counterpart. It is shown that the estimated VTEC values obtained from the developed models agree to within 4 TECU (RMS) with the IGS-GIM counterparts.

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1. INTRODUCTION

Ionosphere is the layer of freely charged electrons quantified by the total electron content (TEC). The slant TEC is the total number of electrons along the line-of-sight between the satellite and the receiver (Figure 1). TEC has a diurnal, a monthly, a seasonal and the so-called 11-year solar cycle variations. It also varies spatially, depending on the geographic location. TEC modeling is an important parameter for space weather and precise positioning applications. Therefore, the global positioning system (GPS) has been used widely in modeling the total electron content on both regional and global scales. Recently, the combined GPS/BeiDou system has also been used in TEC modeling with more visible satellites and better coverage of the ionosphere pierce point (IPP) (Figure 1).

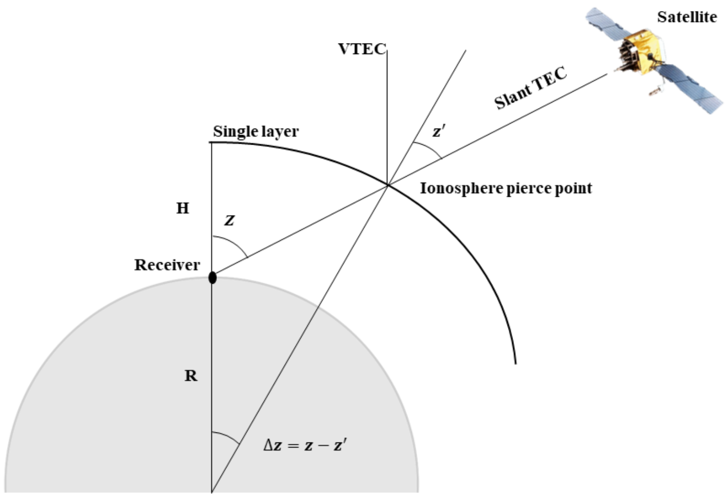

Figure 1 Illustration of slant TEC, VTEC and IPP.

The ionosphere modeling using the GPS observations or the combined GPS/BeiDou observations has been proposed by a number of researchers (e.g., Tang et al., 2014; Wu et al., 2014; Li et al., 2015; Rovira-Garcia et al., 2015; Xi et al., 2015; Yang and Gao, 2015; Zhang et al., 2015; Ren et al., 2016; Xue et al., 2016). Zhang et al. (2015) developed a regional ionospheric mitigation model over China using data from BeiDou only, GPS only, and the combined GPS/BeiDou. In order to validate their model, the VTEC and differential code bias (DCB) were computed and compared with the center for orbit determination in Europe (CODE) counterpart. The findings revealed that the combined GPS/BeiDou model could significantly improve the accuracy of the estimated TEC and the DCB values.

The objective of this study is to develop a regional total electron content estimation model in Europe using the combined GPS/BeiDou observations. The proposed model has spatial and temporal resolutions of 1º×1º and 15 minutes, respectively. GPS/BeiDou observations from 16 international GNSS service (IGS) and IGS multi-GNSS experiment (IGS-MGEX), and EUREF reference stations are processed in the zero-difference mode. The bi-linear expansion function is used to model the VTEC. A least-squares algorithm is developed to estimate the VTEC parameters for a 15-minute time interval. Thereafter, two different interpolation techniques are used in order to determine the VTEC values at 1º×1º grid. The used methods are the inverse distance weighted (IDW) and Kriging, respectively. In order to evaluate the performance of the developed models using the aforementioned methods, the VTEC values are assessed and compared with the IGS global ionospheric maps (IGS-GIM) counterpart. It is shown that the VTEC estimated from the two proposed models are accurate and fit well with the IGS-GIM counterpart with root mean square (RMS) error less than 4 total electron content units (TECU). In addition, the accuracy of the Kriging-based model is superior to the IDW-based model.

2. REGIONAL TEC MODEL DEVELOPMENT

The basic GNSS observation equations can be expressed as follows (Kleusberg and Teunissen, 1998):

$$P_{G1} = \rho_r^G + c(dt_r - dt^G) + I_{r,1}^G + T_r^G + c\left(d_{r,1} + d_1^G\right) + \varepsilon_{G,p,1} \tag{1}$$

$$\mathrm{P_{G2}} = \mathrm{\rho_r^G} + \mathrm{c(dt_r - dt^G)} + \mathrm{I_{r,2}^G} + \mathrm{T_r^G} + \mathrm{c\left(d_{r,2} + d_2^G\right)} + \mathrm{\varepsilon_{G,p,2}} \tag{2}$$

$$P_{B1} = \rho_r^B + c(dt_r - dt^B) + I_{r,1}^B + T_r^B + c\left(d_{r,1} + d_1^B\right) + \varepsilon_{B,p,1} \tag{3}$$

$$P_{B2} = \rho_r^B + c(dt_r - dt^B) + I_{r,2}^B + T_r^B + c\left(d_{r,2} + d_2^B\right) + \varepsilon_{B,p,2} \tag{4}$$

where G and B refer to the GPS and BeiDou satellite systems, respectively; P_{G1} and P_{G2} are the GPS pseudorange measurements on L_1 and L_2, respectively; P_{B1} and P_{B2} are the BeiDou pseudorange measurements on B_1 and B_2, respectively; ρ_r^G and ρ_r^B are the satellite-receiver true geometric ranges; c is the speed of light in vacuum; $I_{r,1}^G$ and $I_{r,2}^G$ are the ionospheric delay on L_1 and L_2, respectively; $I_{r,1}^B$ and $I_{r,2}^B$ are the ionospheric delay on B_1 and B_2, respectively; T_r^G and T_r^B are the tropospheric delay for the GPS and BeiDou systems, respectively; d_r is the code hardware delay for the receiver; d^G and d^B are the code hardware delay for the GPS and BeiDou satellites, respectively; ε_p is the code unmodeled errors, including noise and multipath.

In order to eliminate the geometrical term, tropospheric delay, receiver and satellite clock errors the so-called geometry-free linear combinations are formed using the zero-difference smoothed code observations as follows (Dach et al., 2015):

$$P_{4G} = P_{G1} - P_{G2} = MF \times k_G \times VTEC + c\left(d_{r,1} - d_{r,2}\right) + c(d_1^G - d_2^G) \quad (5)$$

$$P_{4B} = P_{B1} - P_{B2} = MF \times k_B \times VTEC + c\left(d_{r,1} - d_{r,2}\right) + c(d_1^B - d_2^B) + ISB \quad (6)$$

where P_{4G} and P_{4B} are the geometry free combination of the GPS and BeiDou smoothed code observations, respectively; MF is the mapping function; k_G and k_B are frequency-dependent factors for the GPS and BeiDou systems, respectively; ISB is the geometry-free inter-system bias between the GPS and BeiDou systems, which is the difference in code hardware delay between the GPS and BeiDou signals in the receiver channels. The inter-system bias is lumped into the receiver differential code bias for the BeiDou signals. Therefore, the geometry-free formulas can be rewritten as follows:

$$P_{4G} = MF \times k_G \times VTEC + cDCB_{r,G} + cDCB^G \quad (7)$$

$$P_{4B} = MF \times k_B \times VTEC + cDCB_{r,B} + cDCB^B \quad (8)$$

where DCB^G and DCB^B are the differential code bias for the GPS and the BeiDou satellites, respectively; $DCB_{r,G}$ and $DCB_{r,B}$ are the receiver differential code bias for the GPS and the BeiDou systems, respectively. The frequency-dependent factor k can be written as follows:

$$k_G = \frac{40.3(f_{G1}^2 - f_{G2}^2)}{(f_{G1}^2 f_{G2}^2)}, \quad k_B = \frac{40.3(f_{B1}^2 - f_{B2}^2)}{(f_{B1}^2 f_{B2}^2)} \quad (9)$$

where $f_{G1}$and f_{G2} are the carrier phase frequencies on L_1 and L_2 GPS signals, respectively; f_{B1} and f_{B2} are the carrier phase frequencies on B_1 and B_2 BeiDou signals, respectively. The mathematical expression for the mapping function can be defined as follows (Dach et al., 2015):

$$MF = \left[cos\left(arcsin\left(\frac{R}{R+H} sin(z)\right)\right)\right]^{-1} \quad (10)$$

where z is the satellite's zenith distance at receiver; R is the mean radius of the Earth, and H is the height of ionosphere thin shell layer.

The vertical total electron content can be modelled using the bi-linear expansion function depending upon the ionosphere pierce point coordinates and time of epoch, which takes the form (Brunini and Azpilicueta, 2009; Brunini and Azpilicueta, 2010):

$$VTEC(t_{oe}) = a_0(t_{oe}) + a_1(t_{oe}) \times d\lambda + a_2(t_{oe}) \times d\varphi \quad (11)$$

where $VTEC(t_{oe})$ is the ionospheric observable at a time interval t_{oe}; $a_0, a_1$and a_2 are the bi-linear expansion parameters; $d\lambda = \lambda_{IPP} - \lambda_R$ is the difference between the longitude of the IPP and the longitude of the receiver, and $d\varphi = \varphi_{IPP} - \varphi_R$is the difference between the latitude of the IPP and the latitude of the receiver.

Substituting Eq. (11) into Eqs. (7 and 8), the ionospheric bi-linear function can be rewritten as follows:

$$P_{4G}(t_{oe}) = MF \times k_G \times [a_0(t_{oe}) + a_1(t_{oe}) \times d\lambda + a_2(t_{oe}) \times d\varphi] + cDCB_{r,G}(t_{oe}) + cDCB^G \quad (12)$$

$$P_{4B}(t_{oe}) = MF \times k_B \times [a_0(t_{oe}) + a_1(t_{oe}) \times d\lambda + a_2(t_{oe}) \times d\varphi] + cDCB_{r,B}(t_{oe}) + cDCB^B \quad (13)$$

where a_0, a_1, a_2, DCB_r and DCB^s are the unknown parameters to be estimated. For this research, the time interval (t_{oe}) is selected to be 15 minutes. The estimation of the satellite DCB needs a well-distributed network, however, only 16 stations are examined and thus the satellites DCBs for both the GPS and BeiDou available from MGEX website (MGEX-DCB, 2017) are used.

A weighted least squares algorithm is developed to estimate the unknown VTEC and receiver DCBs parameters for 15-mintute time interval, which takes the expression:

$$\boldsymbol{\Omega} = (\boldsymbol{A^T P A})^{-1} \boldsymbol{A^T P l} \quad (14)$$

where the matrices of $\boldsymbol{\Omega}, \boldsymbol{A}$ and $\boldsymbol{l}$ can be expressed as follows:

$$\boldsymbol{\Omega} = \begin{bmatrix} a_0(t_{oe}) \\ a_1(t_{oe}) \\ a_2(t_{oe}) \\ DCB_{r,G}(t_{oe}) \\ DCB_{r,B}(t_{oe}) \end{bmatrix}, \ \boldsymbol{A} = \begin{bmatrix} (MF \times k) & (MF \times k \times d\lambda_1) & (MF \times k \times d\varphi_1) & c & c \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ (MF \times k) & (MF \times k \times d\lambda_n) & (MF \times k \times \Delta\varphi_n) & c & c \end{bmatrix},$$

$$\boldsymbol{l} = \begin{bmatrix} (P_4 - cDCB^{s=1}) \\ \vdots \\ (P_4 - cDCB^{s=n}) \end{bmatrix} \tag{15}$$

where $DCB_{r,G}$ and $DCB_{r,B}$ are the receiver differential code bias for the GPS and BeiDou systems, respectively. The elevation-dependent weighting of the observations are used for the weight matrix ($\boldsymbol{P}$).

Two different interpolation techniques are used in order to estimate the VTEC values at 1º×1º grid spacing, including the inverse distance weighted method and the Kriging method. The mathematical expression for the IDW method can be defined as follows (Jin et al., 2014):

$$TEC_{(X,Y)} = \frac{\sum_{ref=1}^{16} \frac{1}{d^2_{ref\rightarrow(X,Y)}} TEC_{ref}}{\sum_{n=1}^{16} \frac{1}{d^2_{ref\rightarrow(X,Y)}}} \tag{16}$$

where $TEC_{(X,Y)}$ is the estimated VTEC at the grid node; TEC_{ref} is the computed VTEC value at the reference station, and $d_{ref\rightarrow(X,Y)}$ is the distance between the reference station and the grid point.

For the Kriging method, its estimate for the grid point can be defined as follows (Webster and Oliver, 2007):

$$TEC_{(X,Y)} = \sum_{ref=1}^{16} w_{ref}\, TEC(ref) \tag{17}$$

where $TEC_{(X,Y)}$ is the estimated VTEC at the grid node; w_{ref} are the Kriging coefficients for the grid point. The universal Kriging assumes a trend function, which is a combination of unknown coefficients and known function as follows:

$$u(x) = \sum_{h=1}^{h} b_h\, f_h(x) \tag{18}$$

where b_h are the unknown coefficients; $f_h(x)$ is the known function, which is selected to be first-order polynomial function in the point coordinates.

$$u(x) = b_0 + b_1 X + b_2 Y \tag{19}$$

For the unbiased estimation, the Kriging coefficients must fit the following criteria:

$$\sum_{ref=1}^{16} w_{ref}\, u(ref) = u(X,Y) \tag{20}$$

For the detailed steps of the universal Kriging estimation, they can be found in Webster and Oliver (2007).

3. METHODOLOGY

To develop the proposed regional ionospheric model, a regional network consisting of 16 IGS and IGS-MGEX, and EUREF reference stations in Europe are used (Figure 2). The stations are distributed in different latitudes in order to reflect different ionospheric characteristics. GPS/BeiDou observations for three successive days (day of year (DOY) 28, 29 and 30 in 2015) are downloaded (BKG, 2017). The solar activity and geomagnetic activity indices are given in Table 1, including the $F_{10.7}$ and the planetary A_P indices, respectively. It is shown that the solar activity is high, meanwhile, the geomagnetic activity is unsettled in the three examined days.

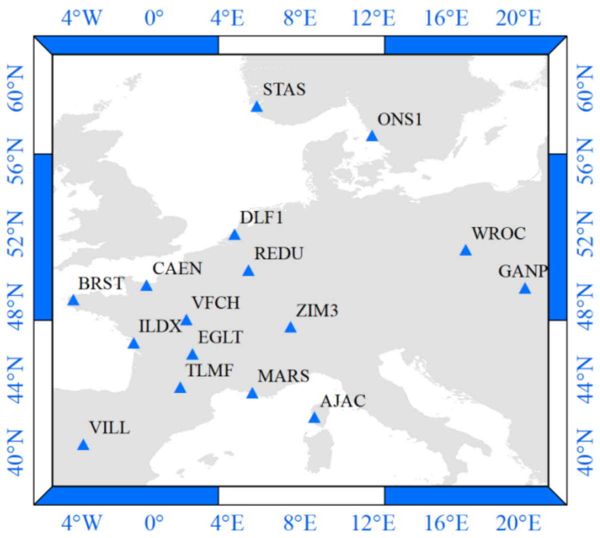

Figure 2 Reference stations distribution.

Table 1 Solar and geomagnetic activity indices for the examined days (OMNIWeb, 2017)

DOY	Solar Flux-$F_{10.7\ cm}$	Geomagnetic index- A_P
28	154.5	7
29	166.7	8
30	154.6	9

Each observation file has a 30-second time interval. The elevation cut-off angle is selected to be 10º. The observation files are processed in the zero-difference mode. The geometry-free linear combination is formed using the smoothed code observations. For the ionospheric mapping function, the effective height (*H*) is selected to be 450 km. In order to produce the RIM, the IGS-MGEX final satellite orbit and clock products are used (MGEX, 2017). For the least-squares estimation (Eqs.14 and 15), the satellite DCB are extracted from the MGEX file (MGEX-DCB, 2017). Then, the station-by-station bi-linear function parameters and the receiver DCBs for each station are assessed.

The proposed model represents the ionosphere variability on the area under consideration in the form of ionosphere exchange format (IONEX). In order to produce the ionospheric map, the vertical total electron content value at the zenith of each reference station is computed using the bilinear expansion function (Eq.11). The expansion coefficient a_0 represents the VTEC value, which is estimated every 15-mintute time interval (Eq.14). Thereafter, the IDW (Eq.16) and the Kriging (Eqs. 17-20) interpolation techniques are used based on the obtained VTEC values from the 16 reference stations. The resulting ionospheric map is determined with 1°×1° grid spacing. The developed RIM is implemented in FORTRAN computer code by the authors.

4. RESULTS AND ANALYSIS

To assess the developed regional ionospheric models using the inverse distance weighted (RIM-IDW) and the Kriging (RIM-K) interpolation methods, the estimated VTEC are compared with the IGS-GIMs (IGS-GIM, 2017) counterpart. Details about the generation and accuracy of the IGS-GIM can be found in Hernández-Pajares et al. (2009). The VTEC values are estimated at 12:00, 14:00 and 16:00 universal time (UT), which are closer to the daily ionospheric activity in the studied area. Figures 3, 4 and 5 show the differences between the IGS-GIM, RIM-IDW and RIM-K models at 12, 14 and 16 UT, respectively, on DOY 30 as an example for the one-day variation analysis.

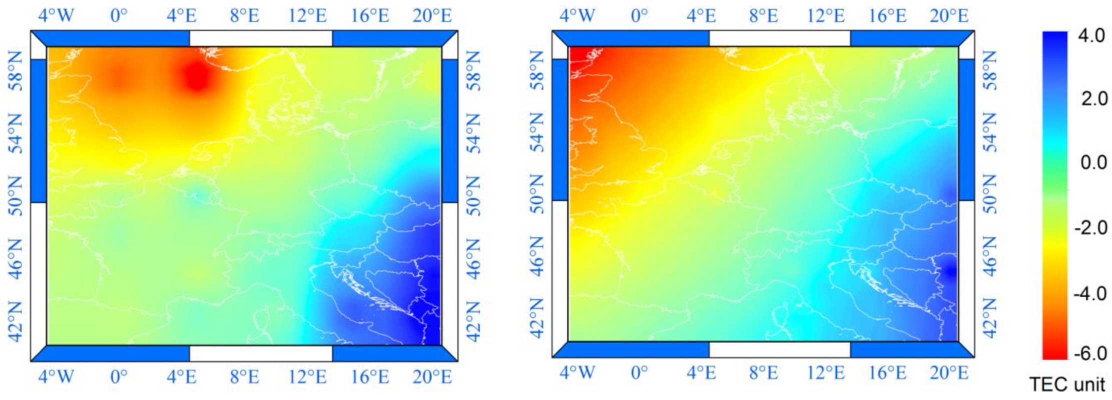

Figure 3 Differences between (a) RIM-IDW and IGS-GIM (left), and (b) RIM-K and IGS-GIM (right) at 12:00 UT on DOY 30.

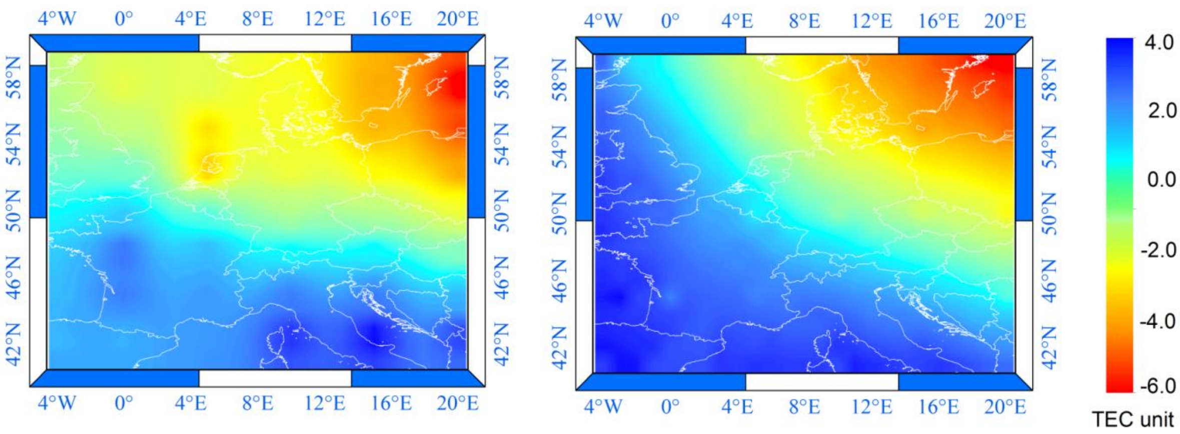

Figure 4 Differences between (a) RIM-IDW and IGS-GIM (left), and (b) RIM-K and IGS-GIM (right) at 14:00 UT on DOY 30.

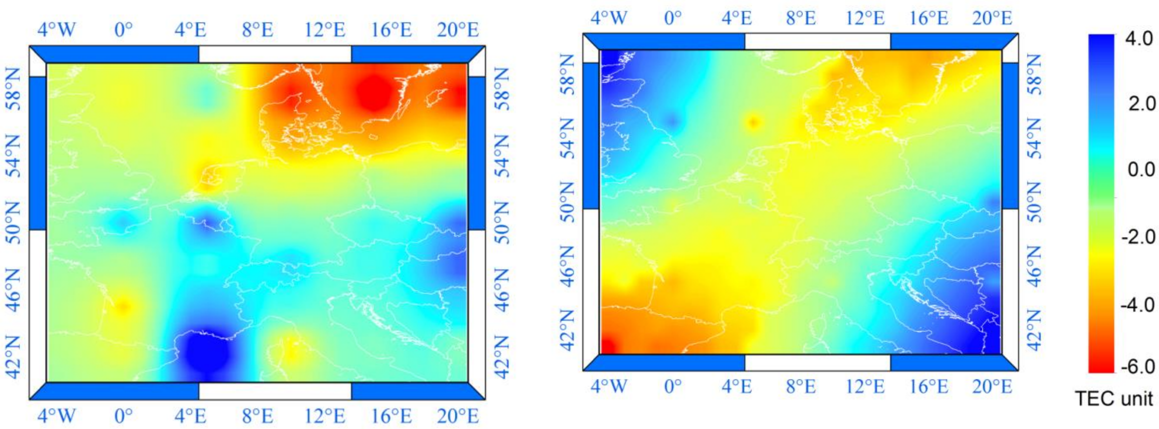

Figure 5 Differences between (a) RIM-IDW and IGS-GIM (left), and (b) RIM-K and IGS-GIM (right) at 16:00 UT on DOY 30.

It can be shown that the VTEC difference for the two models is from -2 TECU up to 2 TECU for most of the area. Meanwhile, the difference is little large in the parts where the station distribution is very sparse. To further evaluate the proposed TEC estimation models, the distribution of the VTEC differences over the studied area at 12:00, 14:00 and 16:00 UT over the examined days (i.e., DOY 28, 29 and 30) are given in Figures 6, 7 and 8, respectively. In addition, the mean and RMS values for the differences are computed and given in Figures 6-8.

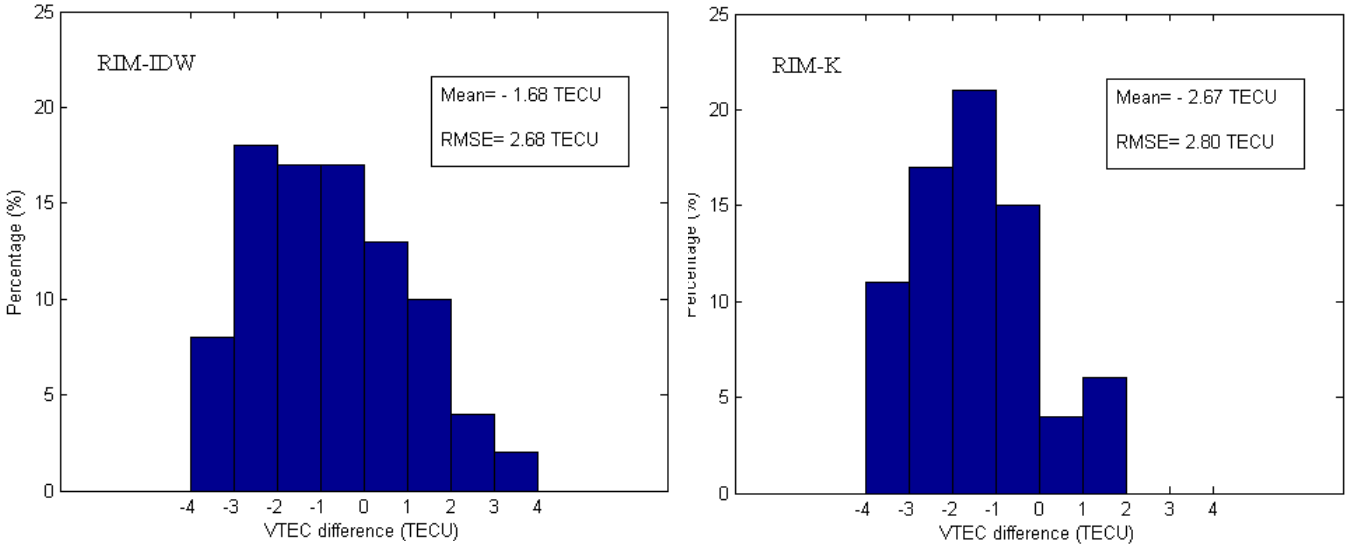

Figure 6 Distribution of VTEC differences over the studied area at 12:00 UT.

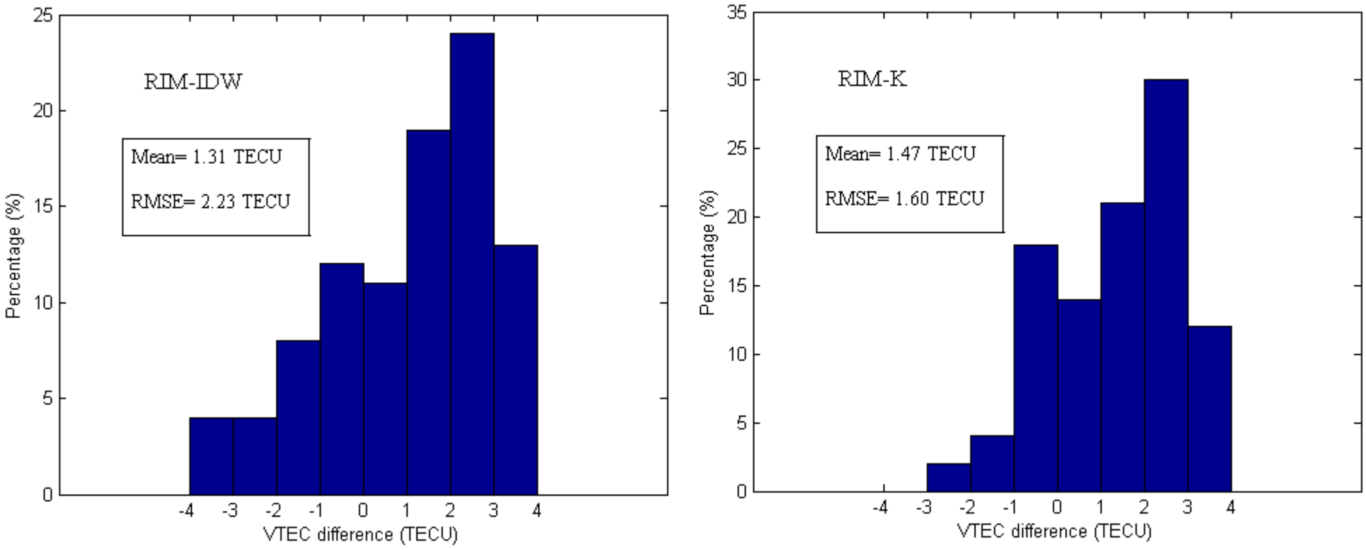

Figure 7 Distribution of VTEC differences over the studied area at 14:00 UT.

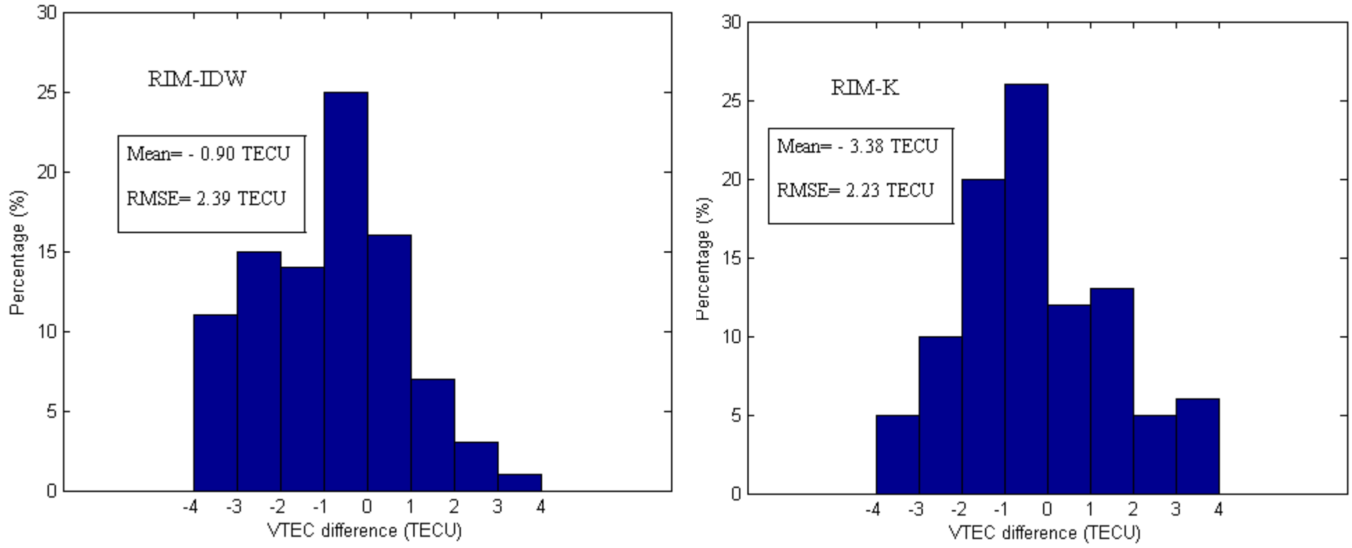

Figure 8 Distribution of VTEC differences over the studied area at 16:00 UT.

It is shown that the estimated VTEC from both of the RIM-IDW and RIM-K models have good agreement with the IGS-GIMs counterpart, where the differences range from – 4 TECU to 4 TECU. In addition, the RMS values are less than 3 TECU. The distribution of the vertical difference for the Kriging-based model is slightly better than that of the IDW-based model. Moreover, the accuracy of the RIM-K model is better than that of the RIM-IDW model, as the RMS values are generally improved.

Figure 9 shows the RMS values for the difference between the IGS-GIM and the proposed models RIM-IDW and RIM-K, respectively. It can be noticed that the RMS values are less than 4 TECU. In addition, the values are somewhat large at 12 UT on DOY 29. This might be attributed to the fact that the solar activity is slightly higher on DOY 29 (Table 1) and the fact that the estimation time (12 UT) is close to the daily ionospheric activity peak over the studied area. It can be said that the agreement of the RIM-K with respect to the IGS-GIM counterpart is better than that of the RIM-IDW.

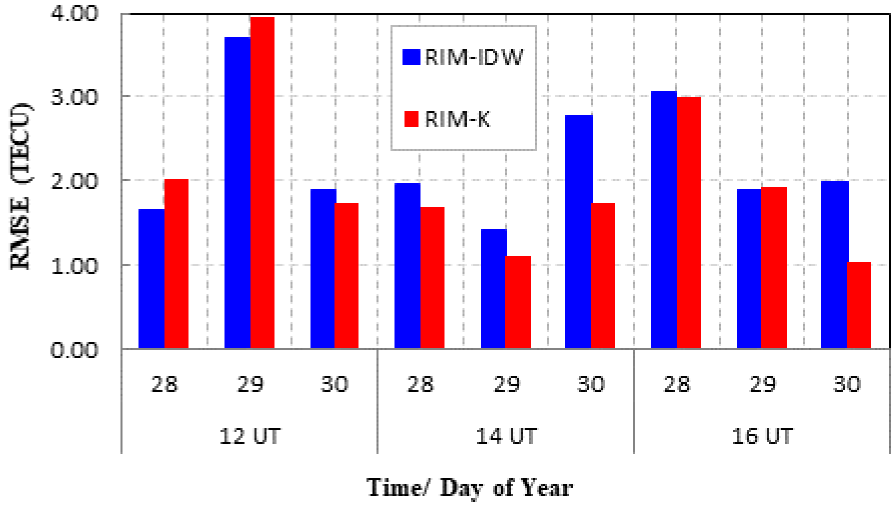

Figure 9 RMS values for the VTEC differences over the examined days.

5. CONCLUSION

In this paper, a regional total electron content estimation model over Europe has been developed using the combined GPS/BeiDou observations. The proposed model has spatial and temporal resolutions of 1°×1° and 15 minutes, respectively. GPS/BeiDou observations from 16 IGS and IGS-MGEX, and EUREF reference stations have been processed in the zero-difference mode. To model the VTEC, the bi-linear expansion function has been used. Thereafter, a least-squares algorithm has been developed in order to estimate the bi-linear parameters for a 15-minute time interval. Two different interpolation techniques have been used in order to estimate the VTEC values at 1°×1° spatial resolution, including the inverse weighted distance and the Kriging methods. To evaluate the accuracy of the proposed model using those methods, the VTEC values have been estimated and compared with the IGS-GIM counterpart. It has been shown that the estimated VTEC values obtained from the developed models agree to within 4 TECU (RMS) with the IGS-GIM counterpart. In addition, the performance of the Kriging-based model is generally better than that of the IDW-based counterpart. It is expected that the developed models will attract a number of applications, including space weather and precise positioning applications.

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