REGIONAL IONOSPHERIC DELAY CORRECTION MODEL FOR SINGLE FREQUENCY PPP USERS IN TURKEY

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ABSTRACT

Ionospheric delay is the major challenge for Single-Frequency Precise Point Positioning (SF-PPP) users. Therefore, a number of organizations have developed ionospheric delay correction products including the International GNSS Service Global Ionospheric Map (IGS-GIM). Unfortunately, however, the IGS-GIM has a limited spatiotemporal resolution, which in turn limits the PPP accuracy. To overcome this limitation, we develop a regional ionospheric delay correction model for SF-PPP users in Turkey. The developed model has spatial and temporal resolutions of 1º×1º and 15 minutes, respectively. GNSS observations from 6 IGS and EUREF reference stations surrounding Turkey are processed using the PPP module in the Bernese 5.2 software package. The resulting model is tested for PPP applications in Turkey. The PPP positioning accuracy and convergence time obtained through the developed model are assessed and compared with those obtained through the IGS-GIM counterparts. The results reveal that the developed regional ionospheric model is found superior to the IGS-GIM model.

Keywords: ionosphere modeling, single-frequency PPP, TEC

1. INTRODUCTION

Ionospheric delay is one of the main error sources in precise point positioning applications. For dual frequency PPP users, ionospheric delay

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can essentially be eliminated using the so-called ionosphere-free linear combination. For single-frequency PPP, however, an ionospheric delay correction model must be used. For this purpose, a number of models are developed for single-frequency PPP applications. A widely-used global ionospheric mitigation model is the International GNSS Service Global Ionospheric Map (IGS-GIM) product. Unfortunately, the IGS-GIM has a spatiotemporal resolution limitation, which may not be adequate for single-frequency PPP users.

A number of regional ionospheric models have been developed by a number of researchers (e.g., Nohutcu et al. (2010); Alothman et al., 2011; Yao et al., 2013; Abdelazeem et al., 2015). Nohutcu et al. (2010) developed a regional ionospheric model over Turkey using the quadratic B-spline function based on GPS observations. Their results were comparable to those obtained through the Bernese software, which uses the spherical harmonic function model. Abdelazeem et al. (2015) developed a real-time regional ionospheric model (RT-RIM) over Europe using the IGS real-time service (IGS-RTS) products. The results showed that their developed model improved the PPP accuracy and convergence time by about 40%, 55% and 40% for the horizontal, height and 3D components, respectively in comparison with the IGS-GIM.

The objective of this study is to develop a Regional Ionospheric Model (RIM) for single frequency PPP user in Turkey. The proposed RIM has spatial and temporal resolution of 1º×1º and 15 minutes, respectively. GNSS observations from 6 IGS and EUREF stations surrounding Turkey are processed using the PPP module in the Bernese 5.2 software package. In order to validate the developed RIM, the Single-Frequency Precise Point Positioning (SF-PPP) accuracy and convergence time obtained through the model are estimated and compared with those obtained through the IGS-GIM. The findings reveal that the developed model improves the positioning accuracy in comparison with the IGS-GIM model.

2. PROPOSED IONOSPHERIC MODEL DEVELOPMENT:

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

$$P_i = \rho_r^s + c(dt_r - dt^s) + I_{r,i}^s + T_r^s + c\left(d_{r,i} + d_i^s\right) + \varepsilon_{p,i} \tag{1}$$

$$\varphi_i = \rho_r^s + c(dt_r - dt^s) - I_{r,i}^s + T_r^s + c\left(\delta_{r,i} + \delta_i^s\right) + \lambda_i N_i + \varepsilon_{\varphi,i} \tag{2}$$

where P_i and φ_i are the pseudorange and carrier phase measurements on frequency i in meter , respectively; ρ_r^s is the satellite-receiver true geometric range; c is the speed of light in vacuum; dt_r and dt^s are the receiver and satellite clock errors, respectively; $I_{r,i}^s$ the ionospheric delay; T_r^s the tropospheric delay; $d_{r,i}$ and d_i^s are the code hardware delay for the receiver and the satellite, respectively; $\delta_{r,i}$ and δ_i^s are the carrier phase hardware delay for the receiver and the satellite, respectively; λ_i is the wavelength of carrier phase; N_i is the non-integer phase ambiguity, and $\varepsilon_{p,i}$ and $\varepsilon_{\varphi,i}$ are the code and phase unmodeled errors, including noise and multipath.
Geometry-free linear combinations are formed using the un-differenced carrier-smoothed code observations, which eliminate the geometrical term, tropospheric delay, receiver and satellite clock errors as follows (Dach et al., 2007):

$$P_4 = P_1^- - P_2^- = \left(1 - \frac{f_1^2}{f_2^2}\right) I_r^s + c(\Delta b^s + \Delta b_r) \tag{3}$$

where P_1^- and P_2^- are the smoothed code observations on L_1 and L_2, respectively; f_1 and f_2 are the carrier phase frequencies on L_1 and L_2, respectively; I_r^s is the ionospheric delay of L1; c is the light speed in vacuum; Δb^s and Δb_r are the differential code bias (DCB) for the satellite and the receiver, respectively.
Based on Equation 3, the slant TEC along the satellite-receiver path can be determined as follows:

$$STEC = \left(\frac{f_1^2 f_2^2}{40.3(f_1^2 - f_2^2)}\right) [P_4 + c\,(\Delta b^s + \Delta b_r)] \tag{4}$$

The vertical TEC is estimated using the Modified Single Layer Model (MSLM) mapping function which assumes that all free electrons are concentrated in a shell of infinitesimal thickness at an effective height H. The effective height H corresponds to maximum electron density at the F2 peak ranges from 350 km to 450 km. The vertical TEC is estimated at the Ionosphere Pierce Point (IPP) as follows (Schaer, 1999):

$$VTEC = STEC * cos\left(arcsin\left(\frac{R}{R+H} sin(\alpha z)\right)\right) \tag{5}$$

where z is the satellite's zenith distance at receiver; R is the mean radius of the Earth; H is the effective height and α is a correction factor. Best fit of the MSLM with respect to the JPL Extended Slab Model (ESM) mapping function is achieved at H = 506.7 km and α = 0.9782, when using R = 6371 km and assuming a maximum zenith distance of 80 degrees (Dach et al., 2007).
In order to model the vertical TEC on a regional scale, the spherical harmonic function is used depending upon the geographic latitude (β) and the sun-fixed (s) longitude of the IPP, respectively (Schaer, 1999):

$$\mathrm{E}(\beta, \mathrm{s}) = \sum_{\mathrm{n}=0}^{\mathrm{n_{max}}} \sum_{\mathrm{m}=0}^{\mathrm{n}} \mathrm{P}_{\mathrm{nm}}^{-}(\sin\beta)\,(\mathrm{a_{nm}}\cos \mathrm{ms} + \mathrm{b_{nm}}\sin \mathrm{ms}) \tag{6}$$

where n_{max} is the maximum degree of the spherical harmonic expansion; P_{nm}^{-} are normalized associated Legendre functions of degree n and order m; a_{nm} and b_{nm} are the unknown coefficients of spherical harmonics.
Substituting Equations 4 and 5 into Equation 6, the spherical harmonic model can be rewritten as follows:

$$\sum_{n=0}^{n_{max}} \sum_{m=0}^{n} P_{nm}^{-}(\sin\beta)\,(a_{nm}\cos ms + b_{nm}\sin ms) = \left(\frac{f_1^2 f_2^2}{40.3(f_1^2 - f_2^2)}\right)[P_4 + c\,(\Delta b^s + \Delta b_r)] * \cos\left(\arcsin\left(\frac{R}{R+H}\sin(\alpha z)\right)\right) \tag{7}$$

where a_{nm}, b_{nm}, Δb^S and Δb_r are the unknowns parameters to be estimated. In order to separate the DCBs of the satellites and receivers, an additional constraint must be used, as follows:

$$\sum_{s=1}^{s=max} \Delta b^s = 0 \tag{8}$$

3. METHODOLOGY:

A regional network consisting of 6 IGS and EUREF stations surrounding Turkey are used in order to develop the regional ionospheric model (Figure 1). GNSS observations for DOY 362 in 2013 have been downloaded (BKG, 2015). The geomagnetic activity is quiet (A_P-index=2), while the solar activity is medium ($F_{10.7}$- index= 130.1) (OMNIWeb, 2015). Each observation file has a 24-hour time span and a 30 second time interval. The elevation cut-off angle is selected to be 15°. The observation files are processed using the PPP module in Bernese 5.2 software package. In order to develop the RIM, the IGS final satellite orbit, satellite clock and earth orientation parameters are used (IGS, 2015) and then are converted into the Bernese formats. The un-differenced code observations are smoothed. In the parameters estimation process, the effective height is selected to be 450 km. In addition, a maximum degree and order equal to 6 of the spherical harmonic expansion are selected with a 15-minute interval. A group of 49 coefficients of the spherical harmonic model is obtained each time epoch. Then, to create the vertical TEC maps a spatial and temporal resolution of 1°×1° and 15 minutes, respectively, are selected.

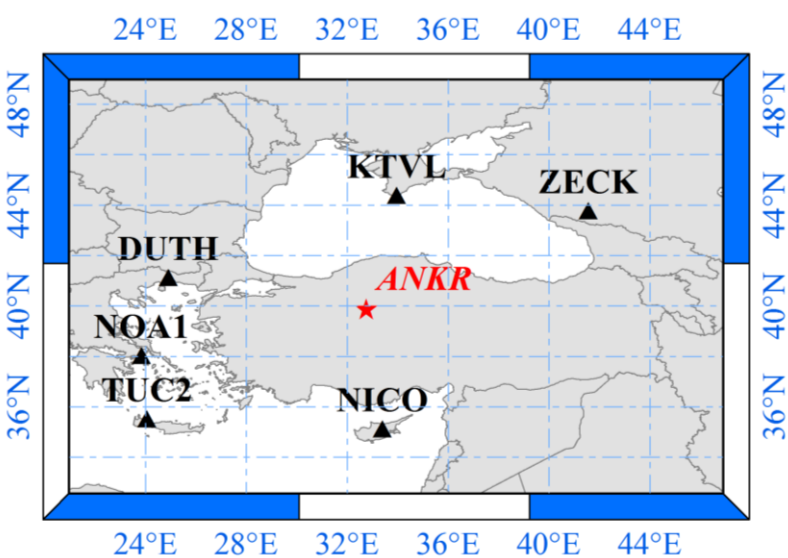
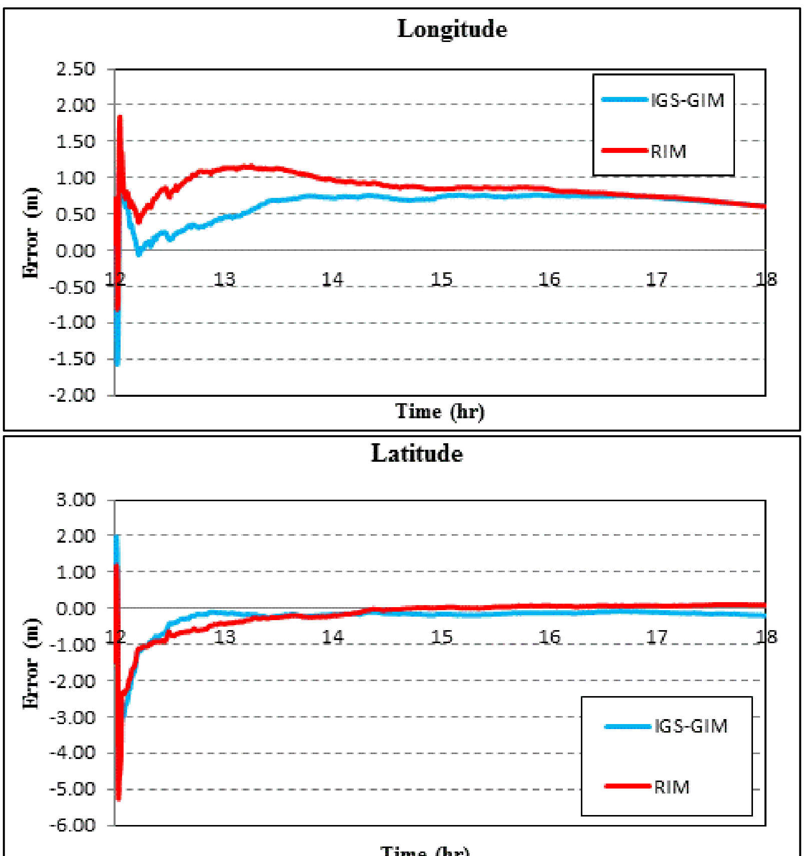


Figure.1 Reference stations distribution (with triangle shape), and examined station (with asterisk shape).

4. RESULTS AND ANALYSIS:

In order to assess the proposed model, GNSS observations from another set of stations in Turkey have been processed using the Natural Resources Canada (NRCan) GPSPace PPP software. Only the results of station ANKR are presented in this paper. The GNSS observation time window has been selected to be 6 hours starting at 12:00 hour in the GPS time frame (i.e. 14:00 local time, which corresponds to the peak ionospheric activity in Turkey). The IGS final precise orbit and clock products have been used to account for the satellite orbit and clock errors, respectively. The tropospheric delay has been accounted for using the Hopfield model with the Neil mapping function. The PPP accuracy and convergence times obtained through the RIM have been estimated and compared with those obtained through the IGS-GIM model.

Figure 2 shows the convergence time for the single-frequency PPP solution using the IGS-GIM and the developed RIM, respectively. It is shown that the proposed model speeds up the convergence time with respect to the IGS-GIM model. In addition, the proposed model has a positioning accuracy better than that of the IGS-GIM counterpart particularly in the height component. This confirms that the RIM represents the ionosphere characteristics better than the IGS-GIM in the area under consideration.



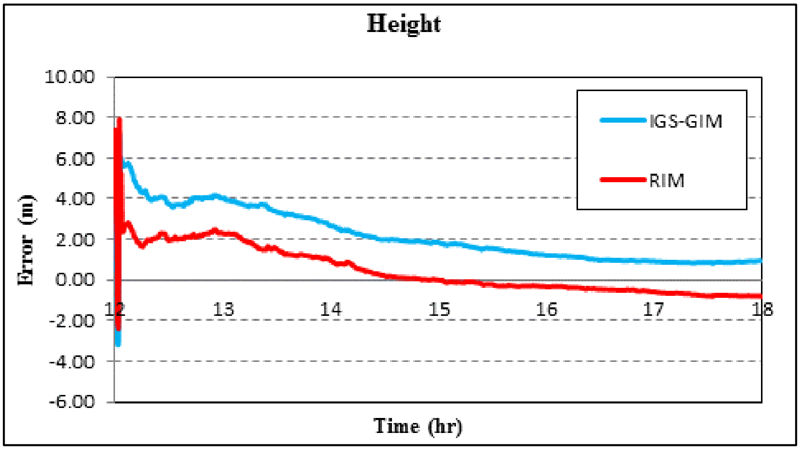


Figure 2 PPP convergence time using the IGS-GIM and the RIM models.

The estimated PPP station coordinates have been compared with those of the EUREF final weekly counterparts. Table 1 summarizes the mean difference for the horizontal and height components.

Table 1 Statistical parameters of the positioning accuracy

Model	Mean (m)	
	2D	Height
IGS-GIM	0.643	0.939
RIM	0.608	-0.811

As shown in Table 1, the positioning accuracy is improved when the proposed RIM is used in comparison with the IGS-GIM model. This is particularly significant in the height component. The horizontal positioning accuracy is improved from 0.643 to 0.608 m. The height error is reduced from 0.939 to 0.811 m.

5. CONCLUSION:

In this study, a regional ionospheric model for single-frequency PPP users in Turkey has been developed. The proposed model has 1°×1° spatial resolution and a 15-minute temporal resolution. GNSS observations from 6 IGS and EUREF reference stations surrounding Turkey have been processed using the PPP module in Bernese software package to develop the model. In order to validate the developed model, the PPP convergence time and positioning accuracy have been assessed and compared with those of the IGS-GIM counterparts. The findings indicate that the developed model accelerates the convergence time. In addition, the positioning accuracy is improved in comparison with the IGS-GIM model.

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