An improved approach to model regional ionosphere and accelerate convergence for precise point positioning

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Abstract

Given the severe effects of the ionosphere on global navigation satellite system (GNSS) signals, single-frequency (SF) precise point positioning (PPP) users can only achieve decimeter-level positioning results. Ionosphere-free combinations can eliminate the majority of ionospheric delay, but increase observation noise and slow down dual-frequency (DF) PPP convergence. In this paper, we develop a regional ionosphere modeling and rapid convergence approach to improve SF PPP (SFPPP) accuracy and accelerate DF PPP (DFPPP) convergence speed. Instead of area model, ionospheric delay is modeled for each satellite to be used as a priori correction. With the ionospheric, wide-lane uncalibrated phase delay (UPD) and residuals satellite DCBs product, the wide-lane observations for DF users change to be high-precision pseudorange observations. The validation of a continuously operating reference station (CORS) network was analyzed. The experimental results confirm that the approach considerably improves the accuracy of SFPPP. For DF users, convergence time is substantially reduced.

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1. Introduction

The ionosphere is a part of the Earth’s atmosphere that extends from the surface of the Earth to an altitude of about 1000 km; the GNSS signals are known to be severely affected by the numerous free electrons along its transmission path through the ionosphere (Klobuchar et al., 1996; Walter et al., 2001; Hunsucker and Hargreaves, 2003; Goodman, 2005; Stankov et al., 2006). Ionospheric effects induce errors must be corrected for positioning and navigation, especially for PPP users (Zumberge et al., 1997; KoubandHérous, 2001; Bishnath and Gao, 2008). Because PPP error sources cannot be eliminated through differential way, most of these, such as satellite orbits, clock errors, tropospheric delays, and site displacement effects can be corrected using publicly available sources, particularly international GNSS services (Beutler et al., 1999; IGS, 2012) or a priori models. The ionospheric errors remain a significant problem. In order to be briefly, we used PPP to indicate DFPPP in the following paragraphs.

To investigate the physical characteristics of ionospheric structures and apply such attributes in the positioning process, researchers proposed different approaches to ionosphere modeling, including empirical, physical, and mathematical modeling (Hochegger et al., 2000; Araujo-Pradere et al., 2004; Schunk et al., 2004; Bilitza and Reinsch, 2008; Strangeway et al., 2009; Buresova et al., 2009). Among these, Klobuchar model broadcast by global positioning system (GPS) satellites, global ionosphere maps (GIM) provided by IGS, and group and phase ionosphere calibration (GRAPHIC) approach is the most widely used by SF users (Klobuchar, 1987; Schaer, 1999; Yunck, 1996). Recently, spatial variations of the ionosphere are taken into account in SFPPP. Bock et al. (2009) proposed a new stochastic ionospheric parameter

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method; in which a stochastic process is used for each satellite to consider the temporal correlation of ionospheric delays. Shi et al. (2012) comprehensively considered the temporal correlation, spatial characteristics, and ionospheric model constraints to improve the performance of SFPPP. However, due to the inaccuracy of ionosphere models or code observations, using the above methods, SFPPP can only achieve decimeter to meter-level positioning. Deng et al. (2009) developed the satellite-specific epoch-differenced ionospheric delay (SEID) model to retrieve tropospheric delays with mixed SF and DF receivers, where ionosphere changes are derived from raw observations of nearby DF receivers. Zou et al. (2010) adapt the SEID model for deformation monitoring. However, SEID model retrieves the ionospheric change which still contains the unknown phase observations ambiguities. This causes it only useful for improving SFPPP accuracy.

The anisotropic ionospheric plasma effects in phase and signal delays at high frequencies can be represented as a rapidly decreasing series in inverse powers of frequency (Bassiri and Hajj, 1992, 1993; Kim and Tinin, 2011). The dispersive properties help eliminate most of ionospheric effects on the ionosphere-free combination for DF receivers (Zumbeerge et al., 1997). However, the linear combination causes float L3 ambiguity, which is difficult to be fixed directly. At the same time, observation noises increase, especially for code observations, a situation that creates the need for more time to achieve PPP convergence. At least 20 min of data are required for positioning of centimeter-level accuracy (Fang et al., 2001). So, approaches to fix integer ambiguity for PPP have recently been comprehensively investigated to shorten initialization time and improve PPP accuracy (Ge et al., 2008; Collins et al., 2010; Laurichesse and Mercier, 2007; Laurichesse et al., 2009; Bertiger et al., 2010; Geng et al., 2010; Lannes and Teunissen, 2011; Loyer et al., 2012). Due to lack of precise atmospheric delay models, these studies indicate that initialization time can only be reduced to about 15 min. Ge et al. (2010) proposed a NRTK strategy using pre-fit undifferenced observation residuals of the reference network to remove biases and recover the integer feature of the ambiguities at user stations. Li et al. (2010) retrieved atmospheric delays as corrections from data derived by a regional dense network to accelerate convergence.

Accurate atmospheric delay models play an important role in both SFPPP and PPP. In this study, we present a novel approach to model the regional ionosphere, then enhance SFPPP accuracy and accelerate PPP convergence. Relatively stable errors, such as receivers’ DCB, wide-lane UPDs, residual single-difference DCB in the satellite clock products are estimated from data derived by regional reference networks. Ionospheric delay is modeled for each satellite and each epoch. Users can use such products to interpolate ionospheric delay: SF users can achieve centimeter-level positioning results for the horizontal component and approximately 1 dm for the vertical component; DF users can convert wide-lane observations to high-precision pseudorange observations to substantially reduce convergence time.

2. Method

2.1. Ionosphere modeling

The basic model for the GNSS carrier phase and pseudorange observations from receiver r to satellite s, in units of length, is

\[ P_r = \rho + c(dT - dT) - \frac{40.309}{f_m^2} S + T + D_r + D^* + \epsilon_p \]  

(1)

\[ L_r = \rho + c(dT - dT) + \frac{40.309}{f_m^2} S + \lambda_m N + \epsilon_L \]  

(2)

where \( P_r \) and \( L_r \) represent the code and phase measurements of the receiver transmitter at a given time \( t \), respectively; \( \rho \), \( dT \), \( T \), and \( S \) are the corresponding distance, receiver and transmitter clock errors, slant total electron content (STEC), and slant tropospheric delay; \( f_m \) refers to the frequency of observations; \( D_r \) and \( D^* \) are the receiver and transmitter inter frequency DCBs, respectively. \( \lambda_m \) represents the wavelength of carrier observations, and \( N \) represents carrier phase ambiguity in cycles (including integer number and float phase instrumental delays).

In order to determine the STEC from GNSS observations, there are mainly three methods. One is to estimate the phase ambiguities simultaneously as parameters of a geometric model of the electron content, which can ensure high accuracy but also cause high complexity. The second is the so-called phase smoothing pseudorange algorithm (Hatch, 1982; Lachapelle et al., 1986; Liu and Gao, 2004); this approach is simple and widely used, but sensitive to the length of the continuous satellite arc and receiver-related model errors, e.g., multipath effects and observational noise. To obtain the balance of precision and efficiency, researchers have proposed different approaches to extract ionospheric delay from the dual frequency pseudorange and phase observations (Hernández-Pajares et al., 2011; Keshin et al., 2006; Zhang et al., 2011). In this paper, we choose the combined observation-decomposition method (see Hernández-Pajares et al. (2011) for details), whose formula is as follows:

\[ L_1 - \frac{\lambda_1 L_2}{2 N_c} (M_w - N_c) = z \text{ION} - D_r + D^* \]  

(3)

where \( L_1 = L_1 - L_2 \), \( N_c = \frac{l_1N_1 - l_2N_2}{f_1 - f_2} \), \( M_w = \frac{l_1L_1 - l_2L_2}{f_1 - f_2} \) \( - \frac{\lambda_1 f_1 + \lambda_2 f_2}{f_1 + f_2} \), \( z \) represents the proportions of ionospheric delay on \( L_1 \) and \( L_2 \). ION represents the ionospheric delay along the signal propagation path. Eq. (3) indicates that precisely determining ionospheric delay necessitates the separation of \( D_r \) and \( D^* \).

In general, in order to simplify the description of TEC distribution and separate DCBs, a thin TEC layer at around 350 km to 450 km is assumed; this layer can be
modeled by spherical harmonics or polynomial functions (Wild, 1994; Schaar, 1999) while all $D_r$ and $D'_r$ are estimated as constant values for each day. However, the ionospheric pierce points (IPPs) from different satellites may be far from one another due to the high TEC layer, even though the modeling area is not geographically large. It’s difficult to simulating such a large area with uneven distribution data. To reduce the accuracy loss of model, Rocken et al. (2000) and Deng et al. (2009) used different methods to build double-difference and undifference ionospheric model. The two methods were based on the same assumption that the ionospheric delays from a set of reference stations to a specific satellite can be fitted by certain functions.

According to this, in this paper we took a two-step approach to model absolute ionospheric delay. First, $D_r$ and $D'_r$ are extracted by the conventional modeling method, in which a low-order spherical harmonics is constructed for a region. To avoid the disadvantage of station distribution correlation, we use the DCB products from center for orbit determination in Europe (CODE) to correct $D'_r$, whose formula is as follows:

$$\text{STEC}(\beta, s) = \sum_{n=0}^{n_{\text{max}}} \sum_{m=0}^{m_{\text{max}}} \hat{P}_{nm}(\sin\beta)(a_{nm}\cos ms + b_{nm}\sin ms) + D_r$$

where $\beta$, $s$ respectively represent geomagnetic latitude and sun-fixed longitude of the user’s IPP; $P_{nm}$ is regularized Legendre series; $M$ represents the mapping function.

Then, $D_r$ and $D'_r$ products are applied in single station estimation, and STEC of the reference station is extracted epoch by epoch for each satellite. When using the ionospheric product in a user station, we first project the STEC onto the TEC layer by using the modified single-layer model (MSLM) (Schaar, 1999), then adopt distance-based linear interpolation (Gao et al., 1997) to interpolate the VTEC of the user IPP.

$$\text{VTEC}_r = \frac{\sum_{n=1}^{n_{\text{max}}} \frac{1}{D_{\text{dis}}}}{\sum_{n=1}^{n_{\text{max}}} \frac{1}{D_{\text{dis}}}} \text{VTEC}_n$$

where $D_{\text{dis}}$ represents the distance from the rover station to the reference station. Through another projection, we can obtain the STEC along the user’s line of sight.

### 2.2. Positioning algorithm

For consistency (either broadcast or precise), satellite orbits and clocks always refer to the ionosphere-free linear combination of the $P_1$ and $P_2$ codes (Le and Tiberius, 2007). Thus, satellite clock products contain the residual DCB error:

$$\frac{f_1}{f_1 - f_2} b_{p1} - \frac{f_2}{f_2 - f_1} b_{p2}$$

where $b_{p1}$ and $b_{p2}$ represent $P_1$ and $P_2$ DCBs, respectively.

Hardware biases occur in satellites and receivers, and receiver biases can be absorbed by receiver clock errors in PPP estimation; these biases do not affect positioning results (Le and Tiberius, 2007). Thus, DF users can directly use clock products, but SF users must apply satellite DCB products to obtain appropriate satellite clock information on chosen frequencies.

For the SF users, when using the precise ionospheric product based on single satellite, the error of this product is assumed to be much smaller than code noise. Therefore, instead of incorporating the ionospheric product to the GRAPHIC approach, it is added to both pseudorange and phase observations. To determine observation weight, accuracy of the ionospheric products was analyzed next.

Ge et al. (2008) analyzed the stability of the wide-lane and narrow-lane UPDs of SD ambiguities and concluded that wide-lane UPDs are highly stable and easily fixed, whereas narrow-lane UPDs vary with time and may be confronted with the risk of ambiguity fixing rate. Therefore we developed a method that used wide-lane UPD and regional ionospheric products to realize rapid PPP convergence. Wide-lane UPDs can be easily obtained from regional tracking stations by following the method proposed by Ge et al. (2008).

The mathematical model of the SD wide-lane observation equation is expressed as follows:

$$\Delta r_{wl}^{kl} = \Delta P_i^{kl} + \Delta c_t^{kl} + \Delta t_{wl}^{kl} + \Delta T_i^{kl} + \Delta \lambda \Delta (\Delta B_{wl}^{kl} + \Delta \delta \varphi_{wl}^{kl})$$

where $\Delta$ represents the SD operator; $i$ is the station number, $k$ and $l$ denote the satellite numbers; $t_{wl}^{kl}$ is the wide-lane observation; $\Delta B_{wl}^{kl} + \Delta \delta \varphi_{wl}^{kl}$ represents the wide-lane UPD, in which $B_{wl}^{kl}$ is the integer part, $\Delta \delta \varphi_{wl}^{kl}$ is the fractional part; $c_t^{kl}$ is the satellite clock; $t_{wl}^{kl}$ and $T_i^{kl}$ denote the wide-lane ionospheric and tropospheric delays, respectively; $\lambda$ is the wavelength of wide-lane observation; $N_{wl}^{kl}$ represents wide-lane ambiguity.

Using wide-lane UPD products for user stations, it is quite simple to fix wide-lane ambiguity. SD ionospheric errors can be directly corrected with ionospheric products. SD tropospheric delay is small and can be accurately estimated. However, the residual DCB errors in satellite clocks cannot be disregarded, as indicated in Eq. (6). DCB products cannot be used in the same manner as SFPPP because the residual DCB errors have different coefficients for $P_1$ and $P_2$. The residual of the two sides of Eq. (7) is the SD residual DCB error. By averaging all the residuals for a given period (e.g., 1 day) and several tracking stations, we can obtain accurate estimates, which are very stable because it is practically a linear combination of satellite DCBs.

$$SD_{DCB} = (\Delta r_{wl}^{kl} - \langle \Delta P_i^{kl} + \Delta c_t^{kl} + \Delta t_{wl}^{kl} + \Delta T_i^{kl} + \Delta \lambda \Delta (\Delta B_{wl}^{kl} + \Delta \delta \varphi_{wl}^{kl}) + \Delta \lambda \Delta (\Delta B_{wl}^{kl} + \Delta \delta \varphi_{wl}^{kl}) \rangle + \Delta \lambda \Delta N_{wl}^{kl})$$

where $SD_{DCB}$ represents SD residual DCB error; $\langle \rangle$ indicates a weighted average of all observations in the continuous arc.

Using the ionospheric, wide-lane UPD, and residual DCB products, wide-lane observations can finally be
converted into high-precision pseudorange observations, Eq. (7) can be simplified to:

$$\Delta L_{w_i}^{kl} = \Delta r_i^{kl} + \Delta t_r^{kl} + \Delta T_i^{kl} - \Delta \nu_i^{kl}$$  (9)

Simultaneously, the ionospheric product is added to $P_1$ as a pseudorange observation because the noise of $P_1$ is smaller than that of $P_2$. Then for DF users, the two observations are combined with the ionosphere-free combination phase observations to estimate positional parameters.

Because wide-lane UPDs and DCBs (of both satellites and receivers) are high stable and predictable, the proposed method can also be used in real-time applications provided that access to real time orbits and clock products are available (Dow, 2007).

2.3. Data processing scheme

We presented the data processing scheme in Fig. 1 on the basis of the discussion above. First the regional ionosphere model is established to obtain receiver DCBs, then the product is used in strengthen product estimation (including ionospheric delay for single satellites, wide-lane UPDs, and SD SDB errors). Finally, the fore mentioned products are applied by PPP users. For real-time application, DCBs and wide-lane UPD products estimated the last day can serve as high-precision priori information.

3. Experimental validation

To evaluate the effectiveness of the proposed approach, we selected a CORS network composed of 35 stations with DF receivers. This network was located in Jiangsu province, China. Data of day 277 to 283 in 2010 were analyzed. We chose 10 stations, whose average separation was about 130 km, as the reference stations. The rest were chosen as the rover stations. The sampling rate of the observations was 15 s. Only the observations on L1 frequency were used in the SFPPP experiment. The IGS final orbits, clocks, and DCBs from CODE were held constant throughout data processing. Fig. 2 illustrated the test network of reference and rover stations, denoted by a solid triangle and circle, respectively.

3.1. Product analysis

The reference station receiver DCBs were excluded from the conventional ionosphere modeling method. Fig. 3 showed the daily differences in mean values of 7 days. The receiver DCBs were highly stable with differences that were generally less than 0.09 m (0.3 ns). They also showed systematic characteristics. This may because that in the DCB estimation processing, we held the satellite DCBs, but indeed, they might be a little different day and day. But it wouldn’t affect positioning results, because they could be absorbed by receiver clock errors in positioning processing.

To evaluate the accuracy of the ionospheric corrections, we compared the epoch differential differences between the interpolated and measured L4 observations. Fig. 4 showed the differences for PRN07 at station bbjr, together with elevation. Generally, the results showed good agreement level (within 0.01 m) at an elevation angle above 30°, but this agreement diminished at lower elevation angles. Therefore,
the observation weight during data processing was according to elevation angle.

In the SFPPP estimation process, we set the observations weight as follows:

\[
e_{a} = \begin{cases} \sin^2(E_a) & \text{if } (E_a > 30^\circ) \land P_p = 100\, e_a, \ P_L = 100 e_a \\ 100 \times e_a & \text{if } (E_a < 30^\circ) \land (E_a > 10^\circ) \land P_p = e_a, \ P_L = 50 \times e_a \\ 0, & \text{if } (E_a < 10^\circ) \land P_p = 0, \ P_L = 0 \end{cases}
\]

where \( E_a \) represents elevation angle; \( P_p \) is the code observation weight, \( P_L \) is the phase observation weight.

The estimated SD wide-lane UPD and residual DCBs were illustrated in Figs. 5 and 6, with the best satellites being PRN03 and PRN19, respectively. Here it can be seen; the residual DCBs in the satellite clock could reach up to a few meters and could not be disregarded. The wide-lane UPD and residual DCBs remained steady for several days, enabling their use in real-time.

3.2. Positioning results

With the ionospheric, wide-lane UPD, and residual DCB products, all the rover stations with 7-day observations were subjected to simulate dynamic positioning process for both SFPPP and PPP solutions. Given the
similarity of results, only DOY 277 and 278 were discussed below.

Fig. 7 showed the time sequences of the SFPQP results for stations bfyz and zjhz, DOY 277, and Fig. 8 showed the residuals of observations of PRN19 for two stations. It can be seen the station distribution significantly affected positioning results. The station distribution for bfyz was better, with an accuracy that reached 3 cm for the horizontal and 7.7 cm for the vertical, the result was almost comparable with PPP. One of the sides of station zjhz had no reference stations, leading to poor interpolation effects. Despite these conditions, deviations for the east and west component are within a decimeter, and 1.7 dm for the vertical. Fig. 8 showed that because of the weight strategy and interpolation effects, residuals of observations were generally within a centimeter when the elevation angle was above 30°, but significantly became larger as the elevation angle got lower. Due to different station distribution, residuals of bfyz were much smaller than those of zjhz.

All rover stations data were processed by three different strategies and compared below. One of the strategies involved using the regional ionospheric product based on single satellite, whereas the others used GRAPHIC algorithm with CODE product and conventional regional product (in which a low-order spherical harmonics was used in modeling). The RMS values of the station coordinates in the east, north, and up components were shown in Fig. 9. NEWs denoted the ionospheric product based on single satellite, and NEWr denoted the conventional regional product.

NEWr performed better than CODE because of more intensive distribution of reference stations, but the average improvements of three components were relatively small,
respectively 8.9%, 0.01%, 12.5%; this is due to that GRAPHIC algorithm more considerably depended on combined observations and was easily affected by code noise. Simultaneously, the average RMS values of the three directions were 3.8, 4.3, and 9.2 cm, respectively, as derived by the NEWs product. Compared with the CODE product, the meaning improvements of three components reached by 63.7%, 63.6%, and 67.8%, respectively.

Fig. 10 showed the time sequence of PPP results for station btju and bthy, DOY 278; which were processed by the traditional PPP algorithm and the new proposed approach. The wine color represented the 3D coordinate deviations were less than 2 dm. For increased intuitiveness, only the first 480 epochs (120 min) were shown in the figure.

It can be seen that for both stations, it took almost 100 epochs (25 min) to converge 2 dm for 3D deviation using the traditional PPP algorithm. While using the new proposed approach, the convergence speeds may be different because of variances in station distribution and wide-lane fixed rate, but the positioning results can easily converges to centimeter-level especially for the horizontal component.

Then convergence time of all rover stations were compared and analyzed. The convergence conditions were set as 3D coordinate deviations less than 1 dm, 2 dm, 5 dm and 1 m respectively (for this epoch and maintain for the next 20 epochs as the minimum convergence requirement). The statistical results were shown in Fig. 11. Using the new algorithm, users can easily achieve sub meter and decimeter-level positioning results. More than 90% of the rover stations could converges to 1m and 5 dm in 5 min. Approximately 50% converged to 2 dm in 5 min and over 80% converged to 2 dm in 10 min, which were more substantially decreases than the traditional PPP algorithm. However, the effect for users converges to 1 dm was limited; this may be due to inaccuracies in the wide lane observations.

4. Discussion and conclusion

In this paper we developed an improved regional ionosphere modeling and rapid convergence method. Receiver DCBs were extracted from tracking stations, and then ionosphere model was constructed for each satellite. The ionospheric product is absolutely delay, it can be applied both in SFPPP and PPP. For rapid PPP convergence, we estimated the wide-lane UPD and residual DCB in the satellite clock, and used the entire product in position estimation.

The proposed method was experimentally validated with data from a regional CORS network. In the SFPPP experiment, the average RMS values generated by the proposed
approach were 3.8, 4.3, and 9.2 cm for the east, north, and vertical components, respectively. Compared with the GRAPHIC method, the average improvements for the three components reached by 63.7%, 63.6%, and 67.8%.

For DF users, the convergence time was significantly reduced; approximately 50% of the rover stations could converge to 2 dm in 5 min, 80% in 10 min.

The wide-lane UPD and DCBs (both the receivers and residuals in the satellite clock) exhibit highly stable characteristics, indicating that the proposed method can be used in real-time applications. The ionospheric product is the only component that needs updating at high frequencies, a feature that favors real-time data transmission.
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