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REVIEW

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An alternative integer recovery clock method for precise point positioning with ambiguity resolution

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Abstract

When using Global Navigation Satellite System (GNSS) measurements, Precise Point Positioning with Ambiguity Resolution (PPP-AR) has been a popular substitute for relative positioning in geoscience applications. Compared with the Fractional Cycle Biases (FCB) method, the processing of Integer Recovery Clocks (IRC) products estimate, especially for ambiguity datum fixing, is so complex that its application has been greatly limited. Based on the concept of "carrier range", we introduce an efficient way to implement the IRC method, termed as the alternative IRC method in this paper. In this method, the fixed ambiguities derived from PPP-AR using the FCB method, and not a fixed-ambiguity datum, are fixed in the IRC products estimate. This greatly reduces the complexity of implementing the IRC method and does not influence the accuracy of positioning. The alternative IRC method outperforms the FCB method by corroborating the consistency of daily positions in nature with international GNSS service weekly solution. To confirm this improvement, global positioning system measurements acquired over a year (2016) from approximately 500 globally distributed stations were processed. The accuracy of IRC products is approximately 20 ps and is highly stable for this year. Moreover, comparing the positioning accuracy of the FCB method to the alternative IRC method, we find that the mean root mean square over the year falls evidently from 2.03 to 1.65 mm at the east component. Therefore, we suggest that the alternative IRC method should be implemented when estimate IRC products.

Keywords: PPP-AR, Alternative IRC method, Carrier range, FCB methods

Introduction

Precise Point Positioning (PPP) (Zumberge et al. 1997) with Ambiguity Resolution (AR) (PPP-AR) (Bertiger et al. 2010; Collins et al. 2010; Ge et al. 2008; Geng et al. 2012; Laurichesse et al. 2009) for Global Navigation Satellite System (GNSS) measurements is a popular alternative to relative positioning in many geoscience applications, as it does not have the constraint of needing a reference station. Applications include seismic ground deformations (Galetzka et al. 2015), Global Positioning System (GPS) meteorology (Ding et al. 2017) and sea-level monitoring (Fund et al. 2013), where greater positioning accuracy is demanded by the International Terrestrial Reference Frame (ITRF) (Altamimi et al. 2016). Currently, PPP-AR methods can be divided into two main categories. The first, based on corrections using Uncalibrated Phase Delays (UPD) or Fractional Cycle Biases (FCB), is the "FCB method" (Bertiger et al. 2010; Ge et al. 2008; Geng et al. 2012). The second, based on Integer Recovery Clocks (IRC) or decoupled clocks, is the "IRC method" (Collins et al. 2010; Laurichesse et al. 2009). Aside from the FCB/UPD and IRC method, there is another way to realize PPP-AR, that is, by estimating the corrections based on undifferenced and uncombined observables (Geng et al. 2019b; Li et al. 2018). In this method, phase bias is estimated based on an uncombined model, while the phase bias products are also estimated through averaging the fractional parts of combined or raw ambiguities.

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To resolve the singular solution in estimating phase clocks, IRC method choose a subset of ambiguities to fix and provide a replacement datum for the integer recovery clocks (Collins et al. 2010; Laurichesse et al. 2009). In the products estimating strategy, IRC method are more rigorous than FCB method. Because FCB method calculate FCB products with an ambiguity-float network solution, not an ambiguity-fixed network solution. Compared with FCB method, the processing of IRC products requires the estimation of a new clock to absorb the phase biases. The new clock is estimated through averaging the fractional parts of float ambiguities, which is difficult and complex. However, the updated clock with fixed ambiguities can greatly improve the accuracy of the PPP-AR products (Geng et al. 2019a). In this paper, we also update the pseudorange clock to an integer recovery clock. Meanwhile, the IRC method need to choose a subset of ambiguities to fix in the process of integer clock estimation. The choice of ambiguity fixed datum is complex and requires skill (Blewitt 2008). In this paper, we try to simplify this process and reduce the difficulty of implementing the IRC method, whilst ensuring it does not affect the accuracy of PPP-AR products.

Blewitt et al. (2010) developed a new approach for processing massive networks by converting carrier-phase observations to so-called "carrier range" using the Double-Differenced (DD) integer ambiguities resolution, based on fixed-point theorems. Based on this concept, the right integer ambiguities can also be obtained with PPP-AR for converting carrier phase to carrier ranges (Chen et al. 2014). Drawing on this method, we introduce a less complex process for implementing the IRC method, which we have named the "alternative IRC method". This method has been developed by Geng (2010). In this method, instead of fixing a subset of ambiguities to provide a replacement datum for the phase clocks, the integer ambiguities derived from PPP-AR with FCB method are fixed in IRC products estimate. This greatly reduces the difficulty in implementing the IRC method, and does not influence the accuracy of positioning.

Considering that not all users require information about the detailed satellite clocks estimation, we previously released supporting phase biases products and phase clocks (ftp://igs.gnsswhu.cn/pub/whu/phasebias) (Geng et al. 2019a). In order to provide a superior high-accuracy positioning service, we designed open-source FORTRAN software for GPS post-processing PPP ambiguity resolution, named the PRIDE PPPAR, hosted on GitHub (https://github.com/PrideLab/) and the PRIDE-Lab homepage (http://pride.whu.edu.cn) for efficient access (Geng et al. 2019b).

This paper is organized as follows. After the "Introduction" section, the alternative IRC method is addressed theoretically in section "Methods". Thereafter, the experimental methods are described in section "Data processing", and the results after processing are presented in section "Results and discussion". Finally, the conclusions are summarized in section "Conclusion".

Methods

We first present the theoretical fundamentals of PPP-AR and then review the PPP-AR method at the network end. Finally, we demonstrate how we can estimate IRC.

Theoretical fundamentals of PPP-AR

After correcting for antenna phase center offsets and variations (Schmid et al. 2016), and phase wind-up effects (Wu et al. 1992), the GPS pseudorange and carrier-phase ionosphere-free combination observables from the receiver r to the satellite s at a particular epoch are the following:

$$\begin{cases} P_{1,r}^{s} = \tilde{\rho}_{r}^{s} + c \cdot \mathrm{d}\tilde{t}_{r} - c \cdot \mathrm{d}\tilde{t}^{s} + \tilde{\gamma}_{r}^{s} + b_{1r}^{s} \\ P_{2,r}^{s} = \tilde{\rho}_{r}^{s} + c \cdot \mathrm{d}\tilde{t}_{r} - c \cdot \mathrm{d}\tilde{t}^{s} + g^{2}\tilde{\gamma}_{r}^{s} + b_{2r}^{s} \\ L_{1,r}^{s} = \tilde{\rho}_{r}^{s} + c \cdot \mathrm{d}\tilde{t}_{r} - c \cdot \mathrm{d}\tilde{t}^{s} - \tilde{\gamma}_{r}^{s} + \lambda_{1}N_{1,r}^{s} + B_{1r}^{s} \\ L_{2,r}^{s} = \tilde{\rho}_{r}^{s} + c \cdot \mathrm{d}\tilde{t}_{r} - c \cdot \mathrm{d}\tilde{t}^{s} - g^{2}\tilde{\gamma}_{r}^{s} + \lambda_{2}N_{2,r}^{s} + B_{2r}^{s} \end{cases} \tag{1}$$

where r denotes receiver flag; s denotes satellite flag; for brevity, $i = 1, 2$ denote frequency; $P_{i,r}^{s}$ and $L_{i,r}^{s}$ respectively denote pseudorange and carrier-phase measurements in the unit of length; $\tilde{\rho}_{r}^{s}$ denotes a non-dispersive term that includes the geometric distance, the tropospheric delay and the relativity effects; $\tilde{\gamma}_{r}^{s}$ denotes first-order ionospheric delay; $g = f_1/f_2$ where f_1 and f_2 denote the signal frequency for L_1 and L_2, respectively; λ_1 and λ_2 denote the wavelength for L_1 and L_2, respectively; $b_{i,r}^{s}$ and $B_{i,r}^{s}$ respectively denote the pseudorange and carrier-phase hardware biases; $b_{i,r}^{s} = b_{i,r} - b_{i}^{s}$ and $B_{i,r}^{s} = B_{i,r} - B_{i}^{s}$; $b_{i,r}$ and $B_{i,r}$ are for the receiver whereas b_{i}^{s} and B_{i}^{s} are for the satellite; $N_{i,r}^{s}$ denotes the integer ambiguity; the residual or unmodelled errors such as higher-order ionospheric effects and multipath are ignored for brevity.

When we estimate satellite clock corrections with network solutions the pseudorange hardware biases $b_{i,r}^{s}$ are normally lumped into other parameters (Guo and Geng 2018; Xiang and Gao 2017) and divided into two parts (Geng and Bock 2016). One part is a non-dispersive term denoted by x_{r}^{s}; the other part is a frequency-dependence term denoted by y_{r}^{s}:

$$\begin{cases} P_{1,r}^{s} = (\tilde{\rho}_{r}^{s} + c \cdot \mathrm{d}\tilde{t}_{r} - c \cdot \mathrm{d}\tilde{t}^{s} + x_{r}^{s}) + (\tilde{\gamma}_{r}^{s} + y_{r}^{s}) \\ P_{2,r}^{s} = (\tilde{\rho}_{r}^{s} + c \cdot \mathrm{d}\tilde{t}_{r} - c \cdot \mathrm{d}\tilde{t}^{s} + x_{r}^{s}) + g^{2}(\tilde{\gamma}_{r}^{s} + y_{r}^{s}) \end{cases} \tag{2}$$

where

$$\begin{cases} x_r^s = (g^2 b_{1,r} - b_{2,r})/(g^2-1) - (b_2^s - g^2 b_1^s)/(g^2-1) \\ y_r^s = (b_{2,r} - b_2^s - b_{1,r} + b_1^s)/(g^2-1) \end{cases} \tag{3}$$

where x_r^s can also be divided into two parts, one is assimilated into the receiver clock corrections, denoted as $x_r = (g^2 b_{1,r} - b_{2,r})/(g^2-1)$; another is assimilated into the satellite clock corrections, denoted as $x^s = (b_2^s - g^2 b_1^s)/(g^2-1)$; y_r^s is assimilated into ionospheric delays. Generally, ionosphere-free combination observables are used in PPP to eliminate the first-order ionospheric delays in pseudorange and carrier-phase measurements (Dach et al. 2009; Hofmann-Wellenhof et al. 2001). The frequency-dependence part will be eliminated with the first-order ionospheric delays.

$$\begin{aligned} P_{3,r}^s &= \frac{f_1^2}{f_1^2 - f_2^2} P_{1,r}^s - \frac{f_2^2}{f_1^2 - f_2^2} P_{2,r}^s \\ &= \tilde{\rho}_r^s + c \cdot \mathrm{d}\tilde{t}_r - c \cdot \mathrm{d}\tilde{t}^s + x_r^s \end{aligned} \tag{4}$$

Note that the high-order frequency-dependence parts and the high-order ionospheric delays have been neglected. Referring to the pseudorange measurements, similarly, the phase measurements become

$$\begin{aligned} L_{3,r}^s &= \frac{f_1^2}{f_1^2 - f_2^2} L_{1,r}^s - \frac{f_2^2}{f_1^2 - f_2^2} L_{2,r}^s \\ &= \tilde{\rho}_r^s + c \cdot \mathrm{d}\tilde{t}_r - c \cdot \mathrm{d}\tilde{t}^s + X_r^s + \lambda_3 N_{3,r}^s \end{aligned} \tag{5}$$

where $\begin{cases} X_r^s = (g^2 B_{1,r} - B_{2,r})/(g^2-1) - (B_2^s - g^2 B_1^s)/(g^2-1) \\ Y_r^s = (B_{2,r} - B_2^s - B_{1,r} + B_1^s)/(g^2-1) \end{cases}$

$\lambda_3 N_{3,r}^s = \frac{f_1^2}{f_1^2 - f_2^2} \lambda_1 N_{1,r}^s - \frac{f_2^2}{f_1^2 - f_2^2} \lambda_2 N_{2,r}^s$ denotes the ionosphere-free ambiguity named ionosphere-free integer ambiguity, which does not include biases.

As the $\tilde{N}_{3,r}^s$ cannot be removed, the satellite clocks datum is generally provided by the pseudorange (e.g. IGS clock products). As a result, the measurements become:

$$\begin{cases} P_{3,r}^s = \tilde{\rho}_r^s + c \cdot \mathrm{d}t_r - c \cdot \mathrm{d}t^s \\ L_{3,r}^s = \tilde{\rho}_r^s + c \cdot \mathrm{d}t_r - c \cdot \mathrm{d}t^s + \lambda_3 A_{3,r}^s \end{cases} \tag{6}$$

where $c \cdot \mathrm{d}t_r = c \cdot \mathrm{d}\tilde{t}_r + x_r$ and $c \cdot \mathrm{d}t^s = c \cdot \mathrm{d}\tilde{t}^s + x^s$ denote the receiver clocks and the satellite clocks, respectively, which include pseudorange biases; we named these clocks as pseudorange clocks for brevity. $A_{3,r}^s = N_{3,r}^s + X_r^s - x_r^s$ denotes ionosphere-free ambiguity named ionosphere-free float ambiguity, which includes phase biases and pseudorange biases. Generally, we used Eq. (6) to perform float PPP and estimate pseudorange clocks. Moreover, we named the biases part $X_r^s - x_r^s$ as narrow-lane UPDs/FCBs (Ge et al. 2008; Geng et al. 2010). If the UPDs/FCBs products can be obtained, users can determine the PPP ambiguity resolution through Eq. (6).

When the clock products contain the bias part $X_r^s - x_r^s$, Eq. (6) becomes:

$$\begin{cases} P_{3,r}^s = \tilde{\rho}_r^s + c \cdot \mathrm{d}t_r - c \cdot \mathrm{d}t^s \\ L_{3,r}^s = \tilde{\rho}_r^s + c \cdot \mathrm{d}T_r - c \cdot \mathrm{d}T^s + \lambda_3 N_{3,r}^s \end{cases} \tag{7}$$

where $c \cdot \mathrm{d}T_r = c \cdot \mathrm{d}\tilde{t}_r + X_r$; $c \cdot \mathrm{d}T^s = c \cdot \mathrm{d}\tilde{t}^s + X^s$ respectively denote the receiver clocks and the satellite clocks, which include phase biases; we named these clocks as IRC (Collins et al. 2010). If the IRC products can be utilized, users can also determine the PPP ambiguity resolution.

Note that the ionosphere-free ambiguities $N_{3,r}^s$ do not have integer properties. Although we correct the hardware biases X_r^s and x_r^s from Eq. (6), the $N_{3,r}^s$ is also not fixed by the ambiguity search (Teunissen 1998a). In order to realize PPP-AR, the ionosphere-free ambiguity $\lambda_3 N_{3,r}^s$ is usually decomposed into narrow-lane ambiguity $\lambda_n N_{1,r}^s$ and wide-lane ambiguity $\lambda_w N_{w,r}^s = \lambda_1 N_{1,r}^s - \lambda_2 N_{2,r}^s$ (Dach et al. 2009), namely:

$$\lambda_3 N_{3,r}^s = \lambda_n N_{1,r}^s + \frac{f_2}{f_1 + f_2} \lambda_w N_{w,r}^s \tag{8}$$

where $\lambda_n = c/(f_1 + f_2)$ and $\lambda_w = c/(f_1 - f_2)$ denote the narrow-lane and wide-lane wavelengths, which are approximately 11 cm and 86 cm, respectively; f_1,f_2 denote the frequencies of L_1 and L_2, respectively. Because $N_{1,r}^s$ and $N_{w,r}^s$ have an integer character, we can attain the value of fixed ionosphere-free ambiguity $\lambda_3 N_{3,r}^s$ through fixing the wide-lane ambiguities and narrow-lane ambiguities. The narrow-lane ambiguity and wide-lane ambiguity contain UPDs and they lost their integer property; however, the integer characteristic of these ambiguities can be recovered after the UPDs are corrected.

Review of PPP-AR method at the network end

For the FCB method and IRC method, the processing of wide-lane ambiguity is the same at the network end and the users end. Melbourne–Wübbena (MW) combination (Melbourne 1985; Wübbena 1985) is used to obtain fixed integer wide-lane ambiguity and related wide-lane UPDs/FCBs.

$$L_{w,r}^s = \lambda_w \left(\frac{L_{1,r}^s}{\lambda_1} - \frac{L_{2,r}^s}{\lambda_2}\right) - \frac{f_1 P_{1,r}^s + f_2 P_{2,r}^s}{f_1 + f_2} = \lambda_w (N_{w,r}^s + B_{w,r}^s) \tag{9}$$

where L_{wi}^k denotes wide-lane measurements; $N_{w,r}^s$ denotes the fixed integer wide-lane ambiguity; $B_{w,r}^s$ denotes the wide-lane UPDs/FCBs in the unit of a cycle. To reduce the large pseudorange noise, multi-epoch smoothing is used to obtain a more accurate estimate. In order to avoid the influence of receiver FCBs, the difference between satellites is carried out in a wide-lane FCBs calculation. A difference between satellites s and l is:

$$B_w^{s,l} = \left\langle \frac{L_{w,r}^s - L_{w,r}^l}{\lambda_w} - (N_{w,r}^s - N_{w,r}^l) \right\rangle \tag{10}$$

where $\langle\cdot\rangle$ represents averaging over all involved wide-lane ambiguities; the superscript sl denotes satellite s minus l; the subscript r disappears from the FCBs terms because the remaining wide-lane FCBs $B_w^{s,l}$ are only satellite-dependent.

Once the wide-lane FCBs $B_w^{s,l}$ is obtained, the integer wide-lane ambiguities $N_{w,r}^{s,l} = N_{w,r}^s - N_{w,r}^l$ at all involved receivers can also be obtained. Therefore the narrow-lane ambiguity can be calculated by:

$$\lambda_n(N_{1,r}^s + B_{n,r}^s) = \lambda_3 A_r^s - \frac{f_2}{f_1 + f_2}\lambda_w N_{w,r}^s \tag{11}$$

where $N_{1,r}^s$ is the fixed integer narrow-lane ambiguity; $B_{n,r}^s$ denotes the narrow-lane FCBs in the unit of a cycle.

For the FCB method, similarly to Eq. (10), the narrow-lane FCBs can be calculated as wide-lane FCBs (Ge et al. 2008).

$$B_n^{s,l} = \left\langle \frac{(\lambda_3 A_r^s - \frac{f_2}{f_1+f_2}\lambda_w N_{w,r}^s) - (\lambda_3 A_r^l - \frac{f_2}{f_1+f_2}\lambda_w N_{w,r}^l)}{\lambda_n} - (N_{1,r}^s - N_{1,r}^l) \right\rangle \tag{12}$$

where $B_n^{s,l}$ denotes the narrow-lane FCBs.

For the IRC method, we chose a subset of narrow-lane ambiguities to fix and provide a replacement datum for the phase clocks (Collins et al. 2010; Laurichesse et al. 2009). In fact, the narrow-lane FCBs are absorbed into the satellite clock parameter.

Therefore, the Eq. (7) can be written as:

$$\begin{cases} P_{3,r}^s = \tilde{\rho}_r^s + c \cdot \mathrm{d}t_r - c \cdot \mathrm{d}t^s \\ L_{3,r}^s - \dfrac{f_2}{f_1 + f_2}\lambda_w N_{wi}^k = \tilde{\rho}_r^s + c \cdot \mathrm{d}t_r - c \cdot \mathrm{d}t^s + \lambda_n(N_{1,r}^s + X_r^s - x_r^s) \\ N_{1,r}^s = [N_{1,r}^s] \end{cases} \tag{13}$$

Note that, in Eq. (13), the receiver biases can be removed by a single-difference in satellites. We neglect this part to make the equation brief.$N_{1,r}^s$ can be fixed with ambiguity search methods.

Alternative IRC method

The traditional IRC method need to choose a subset of narrow-lane ambiguities to fix and provide a replacement datum for the phase clocks (Collins et al. 2010; Laurichesse et al. 2009). This method is not only complicated, but also has one cycle deviation risk when the ambiguity datum is fixed. The purpose of choosing a subset of narrow-lane ambiguities to fix is to resolve the singular solution in estimating phase clocks.

In view of this, we propose the alternative IRC method. Before we estimate IRC products, we need to realize PPP-AR with FCB method and obtain the fixed ambiguities. Then, we use the fixed ambiguities to transform the phase observations to "carrier range" (Blewitt et al. 2010). This observation does not have ambiguities and maintains the accuracy of the phase observations. Therefore, we can only use the "carrier range" to estimate satellite clocks, named IRC by Laurichesse et al. (2009). Because we do not estimate ambiguities in estimating IRC products, the difficulty of implementing the IRC method is reduced, and this does not influence the accuracy of positioning.

So, we introduce the integer ambiguities $[N_{1,r}^s]$ and $[N_{w,r}^s]$, which are fixed in Eqs. (9) and (13), and recover the ionosphere-free ambiguities $[N_{3,r}^s]$:

$$\lambda_3[N_{3,r}^s] = \lambda_n[N_{1,r}^s] + \frac{f_2}{f_1 + f_2}\lambda_w[N_{w,r}^s] \tag{14}$$

and then using $[N_{3,r}^s]$, we replace the ambiguities in the Eq. (7). Because we have fixed the ambiguities $[N_{3,r}^s]$ and resolved the singular solution in processing by only using phase observations to estimate phase clocks, we can obtain Eq. (15)

$$L_{3,r}^s - \lambda_3[N_{3,r}^s] = \tilde{\rho}_r^s + (c \cdot \mathrm{d}\tilde{t}_r + X_r) - (c \cdot \mathrm{d}\tilde{t}^s + X^s), \tag{15}$$

where $[N_{3,r}^s]$ denotes the integer ambiguities derived from PPP-AR with FCB method. The X_r is relevant to receiver biases, and the X^s is relevant to satellite biases. These biases will be absorbed by the clock parameters. We save the integer recovery clock with a RINEX format as an IGS clock file and send it to the user end. At the user end, we can use wide-lane FCBs products and IRC products directly to fix ambiguities in PPP and obtain the ambiguity resolution. Note that the users can use IRC products to replace the IGS normal clock products.

Data processing

Data and model

All the reference stations from the IGS global permanent network in 2016 (ftp://igs.gnsswhu.cn/pub/gps/data/daily) were used in this study. Additionally, we used the final satellite orbits, 30-s satellite clocks, Earth rotation parameters and P1-C1 differential code biases products released by the Center for Orbit Determination in Europe (CODE) (Dach et al. 2009). Note that use of the CODE final products, rather than the IGS final products, is to avoid potential inhomogeneity of the IGS combination products which may degrade the positioning quality of PPP (Teferle et al. 2007). To maintain consistency between the CODE products and our software, we re-estimated the satellite clocks in the FCB-based method by fixing the satellite orbits, the ERPs and the CODE-based ambiguity-float positions (Geng et al. 2010). These new satellite clocks were then fixed along with the satellite orbits and the ERPs. The data processing models are listed in Table 1.

Station selection strategy

As data from IGS reference stations varies from day to day, if a constant global network is chosen to estimate clock products and FCBs products then missing some key stations will degrade the accuracy of products and affect the results of PPP-AR. Therefore, we present a station selection strategy to choose a global network of stations according to the situation of the stations each day. First, we removed those data files covering less than 12 h of measurements. If data rejection (e.g. low altitude measurements, the epoch of less satellite (<4) and short observation arc) rate is greater than 20%, the station is removed. Second, we used all of the remaining station data to do PPP, and then to obtain the results of PPP float resolution. We will remove those stations with too many (>100) or too few (<30) ambiguities. In our experience, the data quality of such stations is usually bad for estimating products. Finally, we established a global grid with a 5°×5° cell size. Only one station is chosen from each grid cell. Based on the positioning residual and whether or not it had an external clock (e.g. H-Master), we set the priority for each station. Whichever of these has the highest priority in each cell is then chosen. Most grid cells do not contain a station. In the example of the first day of 2016 (Fig. 1), 229 stations are chosen from all of the reference stations, respectively.

Data processing strategy

In data processing, we used approximately 200 stations to estimate PPP-AR products. For the original FCB method, narrow-lane FCBs were estimated every 15 min with 24-h measurements. Note that double-difference ambiguity resolution was applied to obtain highly accurate satellite pair FCB estimates (Ge et al. 2008; Geng et al. 2012). Moreover, the FCB estimates derived from less than 10 stations were deemed unreliable and thus ruled out in this study. The alternative ICR method differs slightly from the previous IRC method proposed by Collins et al. (2010). We fix those right integer ambiguities which come from original FCB method rather than choice ambiguity datum to fix. This is because choosing an ambiguity datum is very complex and existing wrong ambiguities are fixed. This error will cause greater deviation in the pseudorange clock corrections. In order to keep consistent with original FCB method, the IRC derived from less than 10 stations were also deemed

Table 1 Data processing models

Items	Sub-items	Descriptions
Observations	Observation	Ionosphere-free GPS pseudorange and carrier phase measurements
	Prior-constraint	Pseudorange: 0.3 m; Carrier phase: 0.006 cycle
	Cut-off elevation	7°
	Weighting	$p = 1, e > 30°; p = 4\sin^2 e, e \le 30°$ *e* denotes the elevation
Corrections	Phase wind-up	Corrected
	Phase center offset	igs08.atx
	Tidal correction	Corrected (solid tide, polar motion, ocean loading)
	Relativistic correction	Corrected
Parameters	Reference clock	H-master (station)
	Satellite coordinate	Fixed to CODE final products
	Station coordinate	Fixed to PPP daily solusions
	ERP	Fixed to CODE final products
	Zenith troposphere delay	Estimated (GMF) every 1 h
	Horizontal tropospheric gradient	Estimated every 12 h
	Satellite clock	Estimated as white-noise-like parameters
	Receiver clock	Estimated as white-noise-like parameters
	Ambiguity	Estimated as a constants over each continuous session

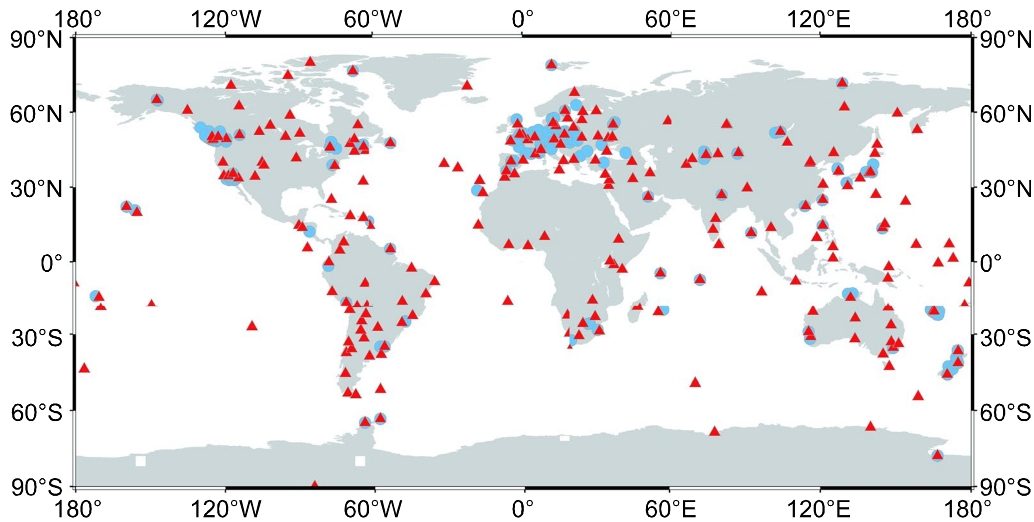

Fig. 1 A global network of stations is denoted by the red triangles and blue circles. The red triangle stations are used to estimate products. The blue circle stations are used to verify the accuracy of the products

unreliable and thus ruled out in this study. The processing flow is shown in Fig. 2.

Results and discussion

PPP-AR with FCB method

Based on the alternative IRC method, the integer ambiguities need to be derived from PPP-AR with FCB method. In order to validate PPP-AR with FCB method, we introduce the distribution of the fractional parts of all the wide-lane and narrow-lane single-difference ambiguities from the network end after having applied the estimated FCBs products in Figs. 3 and 4 respectively.

As shown in Figs. 3 and 4, there is good consistency in the fractional part of all the FCBs-corrected wide-lane and narrow-lane single difference ambiguities. Approximately 97.1% of the residual of those wide-lane ambiguities is distributed in (− 0.15, 0.15) and approximately 97.87% of the residual of those narrow-lane ambiguities is distributed in (− 0.15, 0.15). This will not only increase the accuracy of FCBs products but also improve the success rate of fixing ambiguities.

In order to validate PPP-AR with FCB method, we introduce the success rate of fixing ambiguities in Fig. 5. Because the post-processing pattern is used at the network end, we fix the wide-lane and narrow-lane ambiguities to their nearest integer directly and then use integer bias bootstrapping (Teunissen 1998b) instead of using the lambda method to search and validate these fixed

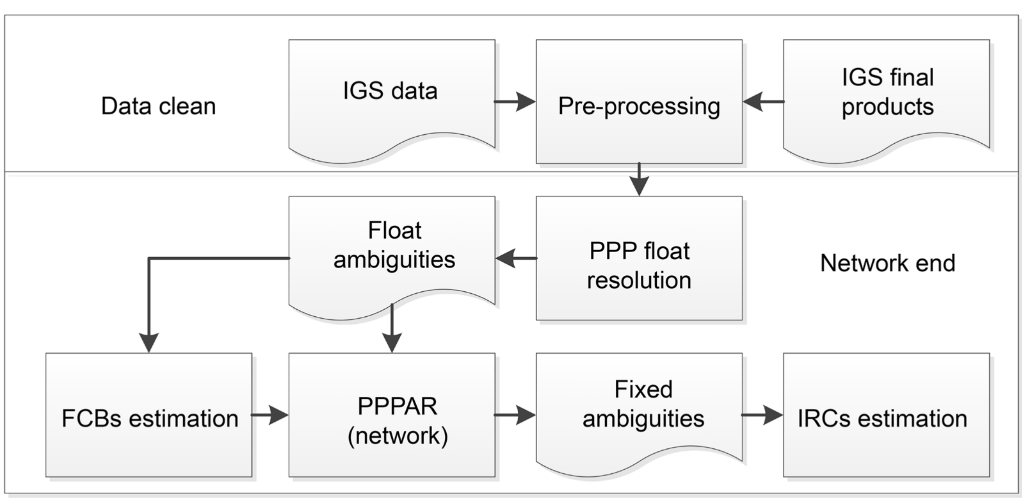

Fig. 2 Processing flow

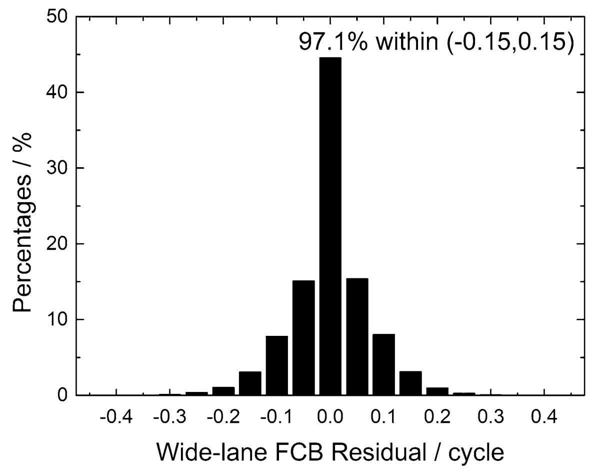

Fig. 3 Distribution of the fractional parts of all the FCB-corrected wide-lane SD-ambiguities. Black is the result from the network of all stations, where approximately 97.1% are close to an integer within 0.15 cycles

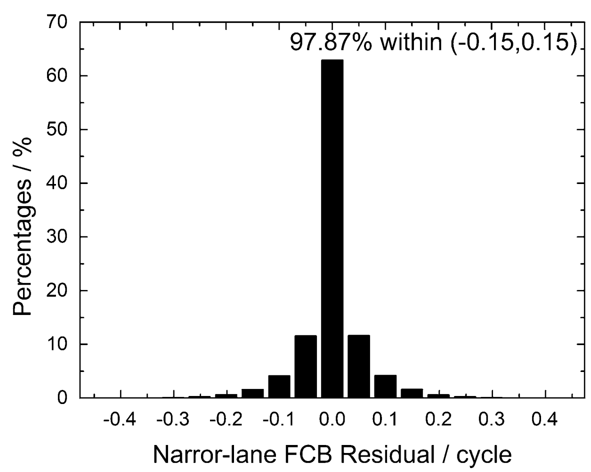

Fig. 4 Distribution of the fractional parts of all the FCB-corrected narrow-lane SD-ambiguities. Black is the result from the network of all stations, where approximately 97.87% are close to an integer within 0.15 cycles

ambiguities. The threshold value of wide-lane ambiguities and narrow-lane ambiguities is 0.2 cycles and 0.15 cycles, respectively.

All of the fixed single-difference ambiguities of the stations involved in estimating FCBs products are considered in Fig. 5. Approximately 87.23% of the fixing rate of the single-difference ambiguity of stations is above 90%, and approximately 95.89% of the fixing rate of the single-difference ambiguity of stations is above 80%. The results show that the calculated FCBs products can effectively realize ambiguity fixed at the network end. Meanwhile,

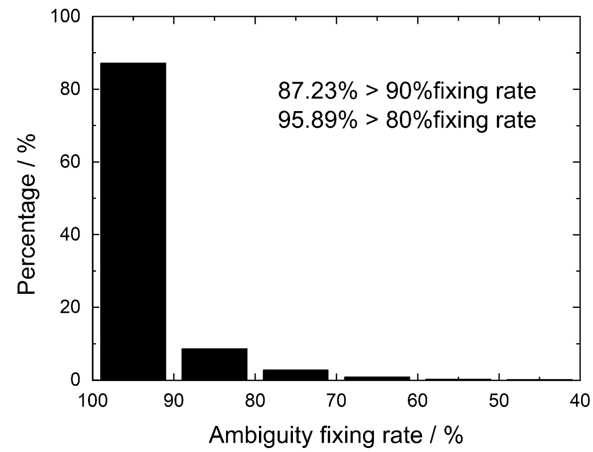

Fig. 5 Ambiguity fixing rate

these FCBs products effectively ensure the correctness of the integer ambiguity when these fixed ambiguities are used in the alternative IRC method.

IRC products with alternative IRC method

After the integer ambiguities derived from PPP-AR with FCB method are introduced into Eq. (14), IRC products are estimated. In order to validate the quality of the IRC products, the Two Times Difference (TTD) method is used to assess the clock corrections (Chen et al. 2017). The clock corrections for G01 are chosen as the reference clock and the final clock products released by CODE are chosen as reference clock products. In total, all of DDT results in 2016 are involved. Outliers within all of DDT results are recognized with a threshold of five times the standard deviation. The average and standard deviation of the remaining results are computed and shown in Fig. 6.

From Fig. 6, it is found that the minimum and maximum average value of all satellites is G11 with 15.12 ps and G24 with 27.65 ps, respectively. The minimum and maximum STD values of all satellites are G11 with 6.32 ps and G13 with 11.81 ps, respectively. We neglect the G04 satellite as a fault. The G32 satellite was replaced in 2016 and cannot be used most of the time, therefore we do not consider this satellite either. By comparing and analyzing these estimated satellite clock corrections, the accuracy of clock corrections is validated.

PPP-AR with alternative IRC method

To assess the accuracy of PPP-AR with the alternative IRC method, we compare the daily solution with the IGS weekly positions. In order to remove the system biases, a seven-parameter Helmert transformation is used. In

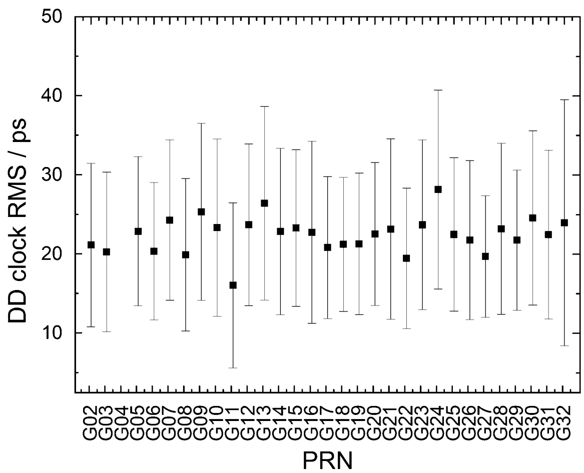

Fig. 6 The accuracy of Phase clock in 2016

total, 350 stations are involved. A threshold of five times the standard deviation is set to reject those abnormal transformed position residuals. Figure 7 shows the RMS of the transformed position residuals based on the alternative IRC method against those based on the FCBs for each day over 1 year. Each point in Fig. 7 represents 1 day.

It can be seen that most points are up the dashed line in the East component, whereas in the other two components no such correlation is seen. Specifically, for the East component, the results clearly have a smaller RMS when employing the alternative IRC method as compared to the FCB method (Calais et al. 2006). Moreover, Table 2 shows the mean of all daily RMS statistics. Compared with float PPP and FCB method, the improvement of the East component is especially obvious. The RMS statistics of the East component with FCB method are 2.03 mm which is clearly decreased to 1.65 mm (a 23% improvement) with the alternative IRC method. Meanwhile, the alternative IRC method can obtain equal accuracy with the traditional IRC method.

Conclusion

In this study, we introduce an easy to implement IRC method named the alternative IRC method, based on the concept of "carrier range". In the alternative IRC method the integer ambiguities derived from PPP-AR with FCB method are fixed in the IRC product estimates. This greatly reduces the complexity of implementing the IRC method and does not influence the accuracy of positioning.

The alternative IRC method outperform the FCB method by corroborating the consistency of daily positions in nature with weekly solutions of the IGS. To confirm this improvement, GPS measurements acquired over a period of 1 year from approximately 500 globally distributed stations were processed. The accuracy of the IRC method is approximately 20 ps and is very stable over 1 year. Moreover, comparing the positioning accuracy of the FCB method with the alternative IRC method, we find that the mean RMS over this year falls

Table 2 Mean RMS of transformed position residuals over 1 year

Solution types	Solution results in different directions (mm)		
	East	North	Up
Float	3.24	1.92	6.16
FCB method	2.03	1.86	5.82
IRC method	1.65	1.84	5.61
Alternative IRC method	1.65	1.84	5.61

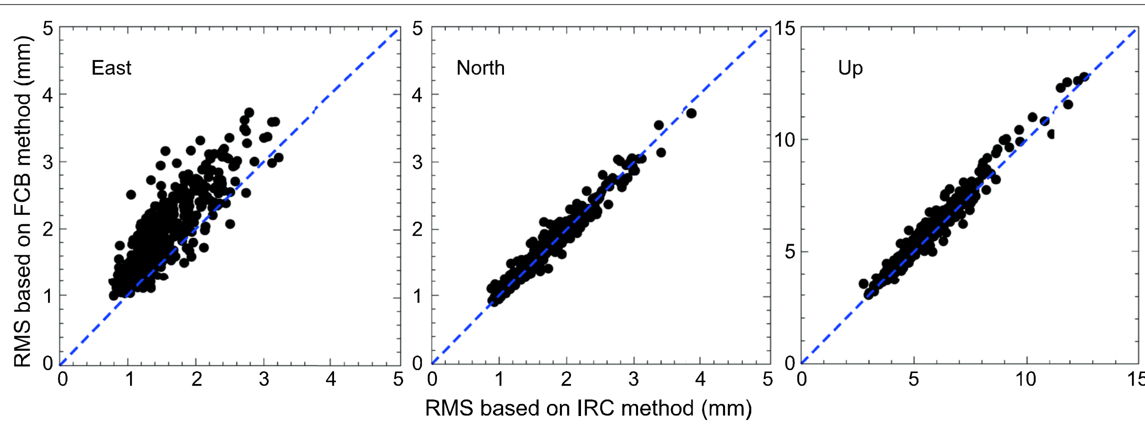

Fig. 7 RMS of the transformed position residuals based on the alternative IRC method against those based on the FCBs for each day over 1 year. Note that the scale for the Up component differs from those for the horizontal components

evidently from 2.03 to 1.65 mm at the east component. Therefore, we suggest that the alternative IRC method should be implemented as demonstrated in this paper.

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Authors' contributions
X.C. devised the project and the main conceptual ideas, worked out almost all of the technical details, and performed the numerical calculations for the suggested experiments; X. C. analyzed the data and wrote the paper. The author read and approved the final manuscript.

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Availability of data and materials
All original data in this article are publicly available. The raw GNSS data and the IGS products can be accessed at ftp://cddis.gsfc.nasa.gov.

Competing interests
The authors declare that they have no competing interests.

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