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# Predicting atmospheric delays for rapid ambiguity resolution in precise point positioning

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## Abstract

Integer ambiguity resolution in precise point positioning (PPP) can shorten the initialization and re-initialization time, and ambiguity-fixed PPP solutions are also more reliable and accurate than ambiguity-float PPP solutions. However, signal interruptions are unavoidable in practical applications, particularly while operating in urban areas. Such signal interruptions can cause discontinuity of carrier phase arc, which introduces new integer ambiguities. Usually it will take approximately 15 min of continuous tracking to a reasonable number of satellites to fix new integer ambiguities. In many applications, it is impractical for a PPP user to wait for such a long time for the re-initialization. In this paper, a method for rapid ambiguity fixing in PPP is developed to avoid such a long re-initialization time. Firstly, the atmospheric delays were estimated epoch by epoch from ambiguity-fixed PPP solutions before the data gap or cycle slip occurs. A random walk procedure is then applied to predict the atmospheric delays accurately over a short time span. The predicted atmospheric delays then can be used to correct the observations which suffer from signal interruptions. Finally, the new ambiguities can be fixed with a distinct WL-LX-L3 (here LX denotes either of L1, L2) cascade ambiguity resolution strategy. Comprehensive experiments have demonstrated that the proposed method and strategy can fix zero-difference integer ambiguities successfully with only a single-epoch observation immediately after a short data gap. This technique works even when all satellites are interrupted at the same time. The duration of data gap bridged by this technique could be possibly extended if a more precise atmospheric delay prediction is found or on-the-fly (OTF) technology is applied. Based on the proposed method, real-time PPP with integer ambiguity fixing becomes more feasible in practice.

*Keywords:* Precise point positioning; Ambiguity resolution; Rapid re-initialization; Atmospheric delay prediction

## 1. Introduction

Precise Point Positioning (PPP) technique (Zumberge et al., 1997) is a focus of the international GNSS community, as it can provide decimeter to centimeter level positioning accuracy globally with no requirement of a dense network of reference stations. It has been widely applied in precise orbit determination, geodesy, aerial photogrammetry, glaciology, GPS meteorology, precise timing, etc. (Kouba and Héroux, 2001; Gao and Shen, 2001; Bisnath and Gao, 2008). However, traditional PPP with float ambiguities requires quite a long convergence time of about 20 min to achieve centimeter-level positioning accuracy, and its reliability is lower than an ambiguity-fixed baseline solution (Han and Rizos, 1996; Wang et al., 2002, 1998a,b). It cannot satisfy some timely applications such as real-time kinematic positioning (Zhang et al., 2011a,b). In order to shorten the initialization time and improve the accuracy and reliability of PPP, some methods for integer-ambiguity-fixed PPP solutions have been proposed in recent years (Ge et al., 2008; Laurichesse et al., 2008; Collins et al., 2008; Bertiger et al., 2010; Li and Zhang, 2012). The reported results showed that initialization and re-initialization time can be shortened to about 15 min by applying the LAMBDA (Teunissen, 1995) method to integer ambiguity resolution in PPP. Positioning

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accuracy at centimeter level can be obtained once the integer ambiguities are fixed.

Although ambiguity fixing can shorten the convergence time of PPP to some extent, in practical applications, especially in an urban area, signal blockage or interruption will result in frequent integer ambiguity resets. Such a long time for fixing new integer ambiguities is not acceptable for most users. If one could fix the zero-difference (ZD) integer ambiguities within seconds, it would be of great benefit for real-time kinematic positioning. Let us recall that in Network Real-Time Kinematic (NRTK) positioning, as most error sources can be eliminated, the integer ambiguities can be fixed and validated very shortly; see, for instance, Section 6.1 and Remark 6.3 in Lannes and Prieur (2013). However, in PPP, clock biases, orbit, and atmosphere delay are significant limitations for rapid ambiguity resolution. In recent years, the quality of orbit and clock from International GNSS Service (IGS) has improved significantly (Dow et al., 2009), the radial accuracy of ultra-rapid orbit is about 5 cm (<http://igscb.jpl.nasa.gov/>). Furthermore, the high correlation between radial orbit component and satellites clocks allows the geometrical errors caused by the orbits to be compensated by clock estimation. Although the predicted satellite clock accuracy of IGS is only at 3 ns level, the real-time estimated and short-term predicted clock accuracy is up to about 0.1 ns, which meets the demands of rapid ambiguity resolution in real-time PPP (Ge et al., 2012; Li et al., 2013). The remaining ionospheric delay should be considered carefully due to the irregularity of its temporal and spatial variation (Deng et al., 2009).

Several PPP–RTK methods have been developed to improve the performance of global PPP service in specific areas by making use of available regional reference networks (Wübbena et al. 2005; Teunissen et al. 2010; Li et al. 2011; Zhang et al. 2011a,b). Let us note in passing that instantaneous ambiguity resolution does not raise any technical problem. A PPP–RTK theoretical framework is also given by Lannes and Teunissen (2011) and Lannes and Prieur (2013). As stressed in those last papers, the variance–covariance matrix of the satellite-clock biases should be used for implementing the PPP mode properly. To the best of our knowledge, this is not done in practice. Concerning the ionospheric delay, its value can be estimated on the grounds of observations at regional reference stations. However, in global PPP ambiguity resolution (PPP-AR), precise atmospheric delay models cannot be derived from the sparse global reference network. Recently, some cycle slip fixing (Banville and Langley, 2009; Zhang and Li, 2012) and rapid re-convergence (Geng 2009; Geng et al., 2010; Li et al., 2013) methods have been proposed to improve the PPP performance. In this contribution, we present a way of estimating accurate ionospheric delays from the ZD ambiguity-fixed PPP solutions in previous epochs and then predict them in a correct way to fill the data gaps. The time-smoothness of the ionosphere (Dai et al., 2003; Teunissen and Bakker, 2012) is exploited for use in rapid ambiguity resolution in global PPP. The performance of the proposed method is demonstrated in different observational environments.

## 2. Ionospheric delay and its prediction

Reducing or eliminating atmospheric delays is important for ambiguity resolution. These delays have to be kept as minimum as possible in order to resolve ambiguities reliably. Ignoring satellite orbit and clock errors, the simplified phase observation equation can be written as follows (Li and Zhang, 2012):

$$L_i^k = \rho_{i_g}^k - I_i^k + T_i^k + f_i + f^k + \lambda N_i^k + \varepsilon_i^k \tag{1}$$

where, the superscript $k$ refers to a given satellite, and subscript $i$ refers to a given receiver; $L_i^k$ could be original phase observations or a combination of phase observations, such as L1, L2, or wide-lane (WL) combination, $\rho_{i_g}^k$ denotes geometric distance, $I_i^k$ is the ionospheric delay, $T_i^k$ is the tropospheric delay, $f_i$ is the uncalibrated fractional offsets (UFOs) related to receiver, $f^k$ is the UFOs related to satellite, $N$ is the ZD integer ambiguity, $\varepsilon$ is the observation noise. Other error components such as the phase center offsets and variations, phase wind-up, relativistic effect, tide loading and so on could be precisely corrected with existing models.

Due to the existence of UFOs originating at receiver and satellite, for a long time only double-differenced ambiguities between satellites and receivers can be fixed. In the recent years, it was demonstrated that satellite UFOs could be estimated from a reference network and applied to other stations for fixing integer ambiguity in PPP mode (Ge et al. 2008; Collins et al., 2008; Laurichesse et al. 2008). Thus, PPP with integer ambiguity fixing requires not only precise satellite orbit and high-rate satellite clock corrections but also UFOs product. Since tropospheric delay can be estimated precisely by introducing zenith path delay (ZPD) parameter in PPP, ionospheric delay is the remaining bias that should be considered carefully (Jin et al., 2010; Jin et al., 2012). In the following sections, we will focus on developing a way to estimate accurate ionospheric delay from epochs where the ambiguities have been fixed and then predict it in a correct manner to fill the data gap.

### 2.1. Epoch-by-epoch ionospheric delay estimation

Provided that (at the end of the initialization stage) the ZD integer ambiguities have been successfully fixed, coordinates and ZPD with cm (even mm) level accuracy can be obtained with the GPS observations collected during the initialization stage at the PPP user end. That means all parameters are accurately known in Eq. (1) except $I_i^k$. Thus, it is straightforward to compute zero-difference ionospheric delay accurately with the following equation:

$$I_i^k = \rho_{i_g}^k - L_i^k + T_i^k + f_i + f^k + \lambda N_i^k + \varepsilon_i^k \tag{2}$$