ACCELERATION OF PPP INTEGER AMBIGUITY RESOLUTION WHEN EMPLOYING IONOSPHERIC DELAYS

ZRYCHLENÍ ŘEŠENÍ CELOČÍSELNÝCH AMBIGUIT V PPP PŘI POUŽITÍ IONOSFÉRICKÝCH ZPOŽDĚNÍ

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Abstrakt

Precise Point Positioning (PPP) je metoda výhodná pro zpracování GNSS dat v případě, že jsou dostupné observace z jediného přijímače. Protože systematické vlivy nejsou eliminovány pomocí diferencí mezi přijímači, je pro přesné určování polohy nezbytné zavádět přesné produkty a modely. Zatímco v případě tradičního PPP, kdy jsou ambiguity řešeny v podobě reálných čísel, jsou potřeba pouze přesné dráhy družic a korekce jejich hodin, pro řešení celočíselných ambiguity (PPP-AR) jsou navíc potřebné i informace o fázových zpožděních družic. Při zohlednění lokálních ionosférických a troposférických parametrů je řešení ambiguity velice rychlé a pomáhá významně redukovat počáteční konvergenci. Při použití těchto přesných korekcí lze řešení považovat za alternativu k populární metodě Real Time Kinematic (RTK), a proto se toto řešení obvykle označuje zkratkou PPP-RTK. Metodami PPP, PPP-AR a PPP-RTK byla zpracována denní GNSS data z Permanentní sítě EUREF (EPN). Troposférické zpoždění nebylo zavedeno jako produkt, ale bylo odhadnuto spolu s dalšími parametry. Vyhodnocení doby konvergence ukázalo významný přínos vyřešených celočíselných ambiguity. Průměrná doba pro dosažení horizontální přesnosti 10 cm byla 22, 11 a 7 minut při zpracování v režimech PPP, PPP-AR a PPP-RTK. První zafixovaná epocha byla v případě PPP-AR a PPP-RTK získána po 10, respektive po 2 minutách. Posouzení přesnosti odhadu STEC (Slant Total Electron Content) odhadnutých na kolokovaných stanicích ukázalo jejich dobrou konzistenci, kterou lze vyjádřit průměrnou směrodatnou odchylkou 0,08 jednotek TEC.

Abstract

Precise Point Positioning (PPP) is a powerful method for GNSS data processing, when observations from only one receiver are utilized. Since any systematic error is not eliminated by between-stations differencing, introduced precise products and models are crucial for precise positioning. While precise satellite orbits and clocks corrections are essential for traditional float PPP, satellite phase biases are required for integer ambiguity resolution (PPP-AR). When considering also local ionospheric and tropospheric parameters, the integer ambiguity resolution is achievable very fast, which helps to reduce the initial convergence significantly. When exploiting such precise atmospheric corrections, the solution can be considered an alternative for the popular Real Time Kinematic (RTK) method. Therefore, the solution is usually abbreviated by PPP-RTK. We processed daily GNSS data from EUREF Permanent Network (EPN) using PPP, PPP-AR, and PPP-RTK. The tropospheric delay was not introduced as a product but estimated together with other parameters. The assessment of the convergence time has

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shown a significant benefit of the resolved integer ambiguities. The average time to reach 10 cm horizontal accuracy was 22, 11, and 7 min when processing in PPP, PPP-AR, and PPP-RTK mode, respectively. The first fixed epoch was obtained after 10 and 2 minutes in the case of PPP-AR and PPP-RTK, respectively. The accuracy assessment of Slant Total Electron Content (STEC) estimated at collocated stations showed their good consistency expressed by the average standard deviation of 0.08 TEC Units.

Klíčová slova

Precise Point Positioning, GNSS, ionosféra, PPP-RTK, ambiguity

Keywords

Precise Point Positioning, GNSS, ionosphere, PPP-RTK, ambiguity

1 Introduction

Precise Point Positioning (PPP) is a widely used method for processing data from the Global Navigation Satellite Systems (GNSS). The traditional form of PPP [1] is based on the ionosphere-free combination of dual-frequency observations, when initial phase ambiguities are estimated as real numbers (float solution). Consequently, PPP needs a relatively long convergence time to achieve high accuracy solution (typically 30 minutes in case of a 30s observation sampling rate). Integer PPP initial ambiguities can be resolved if receiver and satellites hardware-induced delays are known. Compared to the float solution, integer ambiguity resolution (PPP-AR) has two benefits: reduction of an initial PPP solution convergence period and improved positioning stability [2], [3]. PPP-AR based on ionosphere-free observation combination utilizing satellite phase biases typically needs about 20 minutes after a cold start to achieve an accurate solution [4].

The convergence of a state vector can be further reduced by employing precise local atmospheric parameters provided as products from a network solution. We call such solution PPP-RTK [5]. When processing uncombined and undifferenced GNSS observations, the Total Electron Content (TEC) is estimated together with other parameters. The TEC can be estimated at surrounding permanent stations and in particular representation transferred to a user side. Teunissen et al. [6] demonstrated that PPP-RTK could achieve a cm-level horizontal accuracy when using corrections from small-scale networks with inter-station distances of about 60 km. Banville et al. [7] demonstrated sub-decimeter PPP-RTK positioning accuracy when using regional corrections from a network with a minimum distance to the user of 97 km. Zhao et al. [8] demonstrated PPP-RTK convergence of several minutes in a network with an inter-station distance of 209 km.

The goal of this contribution is to compare PPP, PPP-AR, and PPP-RTK in terms of convergence time and coordinates repeatability. We processed GPS-only data from EUREF Permanent Network (EPN) stations. Furthermore, we evaluated PPP-AR and PPP-RTK in case of time to first fix of ambiguities. Finally, we present the accuracy of slant ionospheric delays estimates based on its comparison at the collocated GNSS stations.

2 Methods

The observation equations of dual-frequency ionosphere free combination of code and carrier phase measurements can be written as

$$\begin{aligned} P_{r,IF}^s &= \rho_r^s + c(dt_r - dt^s) + T_r^s + c(b_{r,IF} - b_{IF}^s) + \varepsilon_{r,IF}^s, \\ L_{r,IF}^s &= \rho_r^s + c(dt_r - dt^s) + T_r^s + \lambda_{IF}^s (N_{r,IF}^s + B_{r,IF} - B_{IF}^s) + e_{r,IF}^s, \end{aligned} \quad (1)$$

Where r and s represents receiver and satellites, ρ_r^s denotes receiver-satellite geometric distance, c the speed of light, dt_r and dt^s the receiver and satellite clock offsets, T_r^s the slant tropospheric delay, $b_{r,IF}$ and b_{IF}^s the receiver and satellite code biases, $B_{r,j}$ and B_j^s the receiver and satellite phase biases, $N_{r,IF}^s$ the initial phase ambiguity, λ_{IF}^s the wavelength of ionosphere-free combination, and $\varepsilon_{r,IF}^s$ and $e_{r,IF}^s$ represent the pseudorange and carrier phase measurement noise. The satellite clock offset dt^s is introduced as a product provided for instance by the International GNSS Service (IGS). In the case of traditional PPP, the ambiguities $N_{r,IF}^s$ are contaminated by $B_{r,IF}$ and B_{IF}^s due to strong mutual correlation. Receiver-based hardware delays can be eliminated by between-satellites single differencing. On the contrary, the satellite-based code and carrier phase biases could be estimated by processing data from a permanent network. When such biases are available, the ambiguities can be resolved as integer values.

PPP-RTK is usually based on original uncombined observations at individual frequencies j :

$$\begin{aligned} P_{r,j}^s &= \rho_r^s + c(dt_r - dt^s) - \mu_j I_r^s + T_r^s + c(b_{r,j} - b_j^s) + \varepsilon_{r,j}^s, \\ L_{r,j}^s &= \rho_r^s + c(dt_r - dt^s) + \mu_j I_r^s + T_r^s + \lambda_j (N_{r,j}^s + B_{r,j} - B_j^s) + e_{r,j}^s, \end{aligned} \quad (2)$$

Where, I_r^s is s slant ionospheric delay for the first frequency and $\mu_j = (f_1/f_2)^2$ is the frequency-dependent ionospheric coefficient. The coefficients for GPS L1 and L2 frequency are $\mu_1 = 1$ and $\mu_2 = (77/60)^2$ [9].

With regards to the IGS convention, the satellite clock corrections contain ionosphere-free combination of satellite code biases of two reference signals (e.g., C1W and C2W for GPS). As a result, a particular re-parameterization of dt_r and I_r^s are necessary:

$$\begin{aligned} d\hat{t}_r &= dt_r + \frac{\mu_2}{\mu_2 - 1} b_{r,1} - \frac{1}{\mu_2 - 1} b_{r,2}, \\ \hat{I}_r^s &= I_r^s - \frac{1}{\mu_2 - 1} (b_2^s - b_1^s - b_{r,2} + b_{r,1}). \end{aligned} \quad (3)$$

Slant ionospheric delays can be transformed into the Slant Total Electron Content (STEC) expressed in TEC units (TECU) with

$$I_r^s = \frac{40.3 \times 10^{16}}{f^2} \text{STEC}. \quad (4)$$

3 Data and processing strategy description

For this study, we collected data from 22 collocated GNSS stations (11 pairs, Fig. 1) of the EPN from the period DOY 007 to 031 in 2021. We used daily RINEX 3.xx files with 30s sampling rate. The list of used GNSS stations is summarized in Tab. 1. The table also contains information about GNSS receivers at individual stations and approximate distances between collocated stations.

Fig. 1 Location of used dual GNSS stations.

Tab. 1 Selected EPN GNSS stations.

Station 1	Receiver Type	Station 2	Receiver Type	Distance [m]
BOGO	JPS EGGDT	BOGI	JAVAD TRE_G3T DELTA	107
GOPE	TRIMBLE ALLOY	GOP6	SEPT POLARX5	4
GRAC	LEICA GR25	GRAS	TRIMBLE NETR9	32
IGMI	STONEX SC2200	IGM2	LEICA GR30	20
JOZE	SEPT POLARX5	JOZ2	TRIMBLE NETR9	84
MATE	LEICA GR30	MAT1	LEICA GR30	12
ONSA	SEPT POLARX5TR	ONS1	TRIMBLE NETR9	58
SULD	LEICA GR25	SUL5	TRIMBLE NETR9	11
VIL0	SEPT POLARX5	VIL6	TRIMBLE NETR9	5
WTZR	LEICA GR50	WTZZ	JAVAD TRE_3 DELTA	2
ZIMM	TRIMBLE NETR9	ZIM2	TRIMBLE NETR9	19

We used real-time GNSS orbits, clocks, and satellite code/phase biases provided by National Centre for Space Studies (CNES) via <http://www.ppp-wizard.net/> website, and the consolidated multi-GNSS broadcast ephemerides were provided by the Geodetic Observatory Pecný [10].

We have processed collected GPS code and carrier phase observations by the G-Nut/Geb software [11] when utilizing the PPP, PPP-AR, and PPP-RTK method. We used the Square root forward filter for solving the normal equations, which is a more numerically stable alternative to the traditional Kalman filter. The processing strategy and used models are summarized in Tab. 2.

The PPP-RTK consisted of two steps. First, we estimated STECs for all available satellites based on processing daily uncombined observations at one of the collocated stations (Tab. 1, column 2). Second, we used the estimated STECs as an input to the hourly PPP-RTK processing of data from the second collocated stations (Tab. 1, column 1). In addition, we processed also all GNSS data in PPP and PPP-AR mode.

Theoretically, STECs between-station single-differences are close to zero. Therefore, the accuracy of estimated STECs was assessed based on these differences. Accuracy of the PPP, PPP-AR, and PPP-RTK was also evaluated in terms of convergence time to achieve 10 cm horizontal accuracy. Furthermore, the PPP-AR and PPP-RTK performance were evaluated using the time to first fix (TTFF) indicator defined as a time needed for the first occurrence of the first 10 consecutive epochs with ambiguities successfully resolved as integer values.

Tab. 2 Processing strategy, models, and used precise products.

Item	Parameter
Observation combination	IF combination / uncombined double-frequency
Constellation	GPS only
Sampling rate	30 s
Elevation cut-off	7°
Satellite orbits/clocks/biases	CNES real-time orbits/clock/biases
Ionospheric delay	Eliminated using the IF combination / estimated
Tropospheric delay	Zenith hydrostatic delay: Saastamoinen Zenith wet delay: estimated with 0.5 mm/sqrt(hour)
Ambiguity	Float / fixed
Phase wind-up	Corrected
Attitude of satellites	Nominal models
Antenna phase centers	Corrected with igsR3_2077.atx file

4 Results

Ambiguities fixing rates from daily GNSS processing are shown in Fig. 2. Due to the unavailability of phase biases in the CNES real-time product on DOY 015 and 027, ambiguities on these days could not be fixed. The estimated STECs from the ambiguity fix solution at the VIL6 station on DOY 009 are shown in Fig. 3. Missing STECs data between 21:10 and 22:40 are caused by problems with ambiguities fixing. Negative / close to zero STECs around 6:00 and 19:00 are probably caused due to problems in observing the G04 satellite with the SEPT POLARX5 receiver with firmware version 5.3.0.

Fig. 4 shows single-differences of STECs derived from all visible satellites at VIL0-VIL6 stations throughout the DOY 007-031 period. Missing data on days DOY 015 and 027 are caused by the unavailability of phase biases in the CNES real-time product.

Fig. 2 Ambiguity fixing rate.

Fig. 3 Sample of STEC estimated at VIL0 station on DOY 009 (2021).

Fig. 4 STEC differences at VIL0-VIL6 stations pair.

Based on the STECs single-differences from all station pairs, we calculated the standard deviation of the STEC estimate. Such standard deviations are shown in Fig. 5. The average standard deviation of STEC estimates from all stations over the DOY 007–031 period is 0.08 TECU.

Fig. 5 Precision of STEC estimated at collocated GNSS stations.

Mean convergence times at all stations were calculated from 23 hourly solutions. The estimator needs some time to a precise estimate of parameters (e.g., STECs). Therefore, solutions between 00:00:00–00:59:59 were excluded from the calculations of convergence times due to initial convergence at PPP-RTK reference stations. Fig. 6 shows the average convergence times needed to reach the 10 cm horizontal error of the PPP (left) and PPP-AR (right) solutions. A significantly shorter convergence time can be seen in the case of PPP-AR. Fig. 7 shows PPP-RTK mean convergence times. Compared to PPP-AR (Fig. 6, right), the mean convergence time is shorter here. The average convergence time for all stations in the case of PPP, PPP-AR, and PPP-RTK were 22, 11, and 7 min, respectively.

TTFF of PPP-RTK is significantly shorter compared to the PPP-AR (Fig. 8). The average TTFF was 10 min (20 epochs) in the case of PPP-AR and 2 min (4 epochs) in the case of PPP-RTK, respectively.

Fig. 6 Mean 10cm convergence time PPP (left), PPP-AR (right).

Fig. 7 PPP-RTK mean 10cm convergence time.

Fig. 8 Time to first fix of PPP-AR (left), PPP-RTK (right).

5 Conclusions

We used GNSS data from 22 EPN stations to compare PPP, PPP-AR, and PPP-RTK methods. Observational data from the period between DOY 007 and 031 in 2021 were processed using the G-Nut/Geb software. All GNSS data were processed in PPP, PPP-AR, and PPP-RTK mode on an hourly basis. Input slant ionospheric delays in the case of PPP-RTK were estimated using the daily processing of data from collocated GNSS stations.

The accuracy assessment of ionosphere parameters was based on single differences of STECs estimated at collocated GNSS stations. The evaluation shows a good consistency of estimated STECs. The average standard deviation of STEC estimates from all stations over a processed period was 0.08 TECU.

The assessment of the convergence time has shown a significant benefit of the resolved integer ambiguities. The average time to reach 10 cm horizontal accuracy was 22, 11, and 7 min when processing in PPP, PPP-AR, and PPP-RTK mode, respectively. Comparison of TTFF in the case of PPP-AR and PPP-RTK showed a significant contribution of input STECs to the undifferenced and uncombined PPP-RTK model. The average TTFF of PPP-AR and PPP-RTK were 10 min and 2 min, respectively.

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