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GPS TOOLBOX

PPPLib: An open-source software for precise point positioning using GPS, BeiDou, Galileo, GLONASS, and QZSS with multi-frequency observations

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Abstract
Precise Point Positioning Library (PPPLib) is a multi-GNSS data processing software designed to process multi-frequency data from GPS, BeiDou, Galileo, GLONASS, and QZSS. PPPLib is written in the C/C++ programming language. It can compile and run on both Linux and Windows operating systems. PPPLib mainly performs precise point positioning from single to triple frequency based on either ionospheric-free or uncombined observations. Moreover, it solves for abundant parameters, including position, tropospheric delay, ionospheric delay, and ambiguity information. Useful scripts and visualization tools are also provided for data download, batch processing, or solution presentation. We give a preliminary review, including positioning accuracy and convergence time of PPP using dual-frequency, ionospheric-free from single system to multi-GNSS, to show the working status of the current version of the software. In addition, the software also supports post-processing kinematic mode and INS/GNSS loosely coupled mode for kinematic positioning.

Keywords GNSS · Precise point positioning (PPP) · Multi-frequency · Open-source

Introduction

Global Navigation Satellite Systems (GNSS) are upgraded, and more modernized satellites bring opportunities and challenges to Precise Point Positioning (PPP), which is an absolute positioning technology that can operate on a global scale (Malys and Jensen 1990; Zumberge et al. 1997). Currently, most GNSS satellites are transmitting signals on three or even more frequencies (Li et al. 2020b), e.g., the new Block IIF of Global Positioning System (GPS) can transmit another civil signal L5 (1176.45 MHz) in addition to the existing L1 (1575.42 MHz) and L2 (1227.60 MHz). The GLONASS-K and part of GLONASS-M satellites have started to transmit the G3 signal (1202.025 MHz) with code division multiple access (CDMA) since 2011, while the first and second frequency signals are transmitted by frequency division multiple access (FDMA) technology (Zaminpardaz et al. 2017). China's BeiDou navigation system (BDS) satellites are capable of transmitting signals on multi-bands; frequencies are 1561.098 MHz (B1I), 1207.14 MHz (B2I), and 1268.52 MHz (B3I) for BDS-2 signals. BDS-3 satellites are compatible with BDS-2′s B1I and B3I and broadcast new signals, namely B1C at 1575.42 MHz, B2a at 1176.45 MHz, and B2b at 1207.14 MHz (Yang et al. 2019, 2020), respectively. For the European Union's Galileo system, five frequencies signals are provided, including E1 (1575.42 MHz), E5a (1176.45 MHz), E5b (1207.14 MHz), E5 (1191.795), and E6 (1278.75 MHz) (Tu et al. 2019). Japan's quasi-zenith satellite system (QZSS) provides four signals: L1 (1575.42 MHz), L2 (1227.60 MHz), L5 (1176.45 MHz), and

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LEX6 (1278.75 MHz) (Wang et al. 2019). GNSS is developing to be multi-constellation and multi-frequency, which presents the opportunity to improve positioning accuracy, enhance robustness, and shorten PPP convergence time. Integrated multi-frequency and multi-GNSS will be the future trends of GNSS applications. However, new challenges have arisen in the GNSS community due to the biases induced by new systems and frequencies; furthermore, the computational burden is also an issue for multi-frequency and multi-constellation data processing.

With available multi-frequency signals, GNSS-PPP solutions can be achieved by using single-, dual-, or triple-frequency observations. To meet the demand of single- to multi-frequency users and maximally benefit from multiple constellations, the PPPLib software package has been developed, which is convenient and powerful and can process multi-GNSS data from single to triple frequency. Based on different ionospheric strategies, PPP models can be classified into ionospheric-free (IF) (Zumberge et al. 1997) and uncombined (UC) (Zhou et al. 2018) models. Both models have their own pros and cons. PPPLib supports IF and UC mode to perform PPP solutions from single to triple frequency. However, the inter-frequency clock bias (IFCB) should be carefully handled in triple-frequency processing (Pan et al. 2018). In the current version of the software, PPPLib does not adopt any strategy to deal with IFCB, thus, its limited support for triple-frequency PPP. But the software is continuing to evolve; the bugs that exist in triple-frequency PPP models will be corrected, and its functionality will be improved in future versions.

Although several open-source programs for GNSS-PPP data processing exist, such as RTKLIB (Takasu and Yasuda 2009), GAMP (Zhou et al. 2018), MG-APP (Xiao et al. 2020), and PPPH (Bahadur and Nohutcu 2018), PPPLib will provide some other features, such as a modular, convenient logging system, better efficiency, and a solution visualization tool. The log system includes the following levels: debug (informational events most useful for developers to debug the application), error (error information but will continue the application to keep running), warning (information representing errors in application but application will keep running), and info (mainly useful to represent current progress of application). Each level contains different log information, such as epoch, the value of parameters or calculation matrix. In short, the log system is able to show the whole PPP processing. Thus, the log system will help beginners to understand the PPP processing mechanism more easily. The software also supports post-processing kinematic (PPK) mode and INS/GNSS loosely or tightly coupled mode for real kinematic data processing, as well as PPP ambiguity resolution in the current version. Anyone can get the latest version of PPPLib from https://github.com/heiwa0519/PPPLib and it is also available on the GPS Toolbox website at https://geodesy.noaa.gov/gps-toolbox/. In this paper, the multi-GNSS PPP module will be introduced, and the performance of dual-frequency, ionospheric-free, multi-GNSS PPP will be evaluated. A description of the software is provided in the next section. Subsequently, data processing and comprehensive numerical analyses follow in "Comparison of GNSS combination." Finally, we summarize the main conclusions in the "Summary and conclusions" section.

PPPLib software

PPPLib adopts a post-processing mode for data processing to integrate multi-frequency and multi-GNSS observations. The software is written in C/C++ programming language (version 11.0 or higher) and can be run on Windows and Linux operating systems. It is recommended to compile and run it in the Linux environment for execution efficiency. Instructions on how to compile, install, and run can be found in the User Manual. The overall framework of the software is shown in Fig. 1. The key features of the software include the following:

- Supports multi-GNSS or their combinations with each other
- Standard single point positioning
- University of Calgary PPP Model (Gao and Shen 2002) for single-frequency PPP
- Dual-frequency ionospheric-free/uncombined PPP
- Triple-frequency ionospheric-free with one IF combination or two IF combination mode (no strategy to deal with IFCB, should be improved)
- Triple-frequency uncombined PPP (no strategy to deal with IFCB, should be improved)
- Multi-GNSS post-kinematic processing
- INS/GNSS loosely coupled (under testing)
- INS/GNSS tightly coupled (under testing)
- Support BDS-3 new satellites and signals
- Convenient visualization

The software is powerful for computing the PPP solutions using different GNSS constellations or their combinations with each other, using single-, dual-, and triple-frequency observables. The GNSS-PPP data processing procedure is implemented by three modules in PPPLib as shown in Fig. 2.

The process starts with downloading the required files for performing the PPP solutions, including GNSS observations, precise orbit and clock, EOP, DCB, and ATX as well as reference coordinates file. Then, the SPP algorithm is executed to acquire the approximate coordinates. In the SPP module, a simple strategy is used to detect pseudorange gross errors. If the pseudorange observation of a satellite is marked as having a gross error, this satellite will

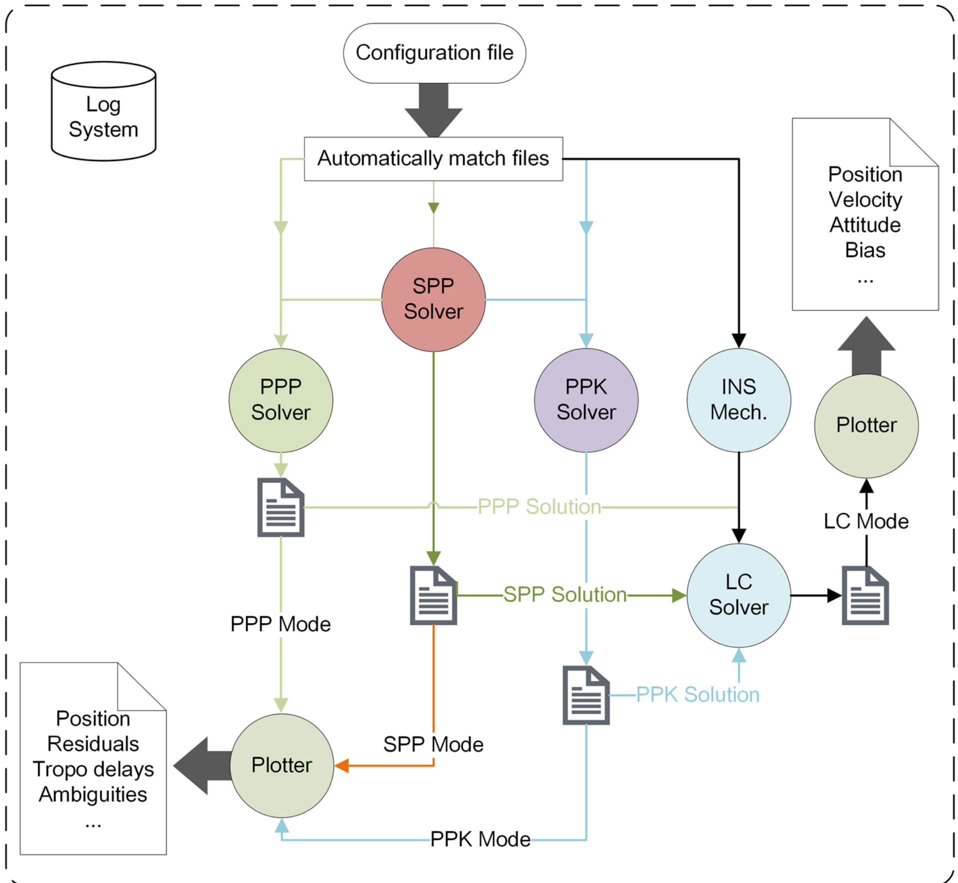

Fig. 1 Overall framework of software. The software supports SPP, PPP, PPK, INS mech and LC positioning mode. (SPP: single point positioning, PPP: precise point positioning, PPK: post-processing kinematic, INS mech: inertial navigation system mechanization, LC: INS/GNSS loosely coupled)

be rejected at that epoch and will not participate in the subsequent processing. The CS detecting method is based on the Hatch-Melbourne-Wübbena combination and geometry-free combination (Blewitt 1990; Hatch 1982). Once a CS has occurred, the corresponding ambiguity parameter should be reinitialized. A robust Kalman filter (KF) algorithm is employed after outlier detection to estimate unknown parameters according to the selected PPP model. In the KF estimator, the coordinates of a station in static mode are considered as constant, while in the kinematic mode, they are modeled as white noise. Normally, the receiver clock is treated as an epoch-wise parameter and the ISBs are estimated as a constant. For tropospheric processing, the zenith hydrostatic delays are corrected by the Saastamoinen model (Saastamoinen 1972) and the zenith wet delays are modeled as a random walk with a process noise of 10^{-8} m^2/s. The global mapping functions (Böhm et al. 2006) are used to project the zenith wet delays to the line-of-sight. Furthermore, in the uncombined PPP models, the ionospheric delay is estimated as a random walk with a process noise of 10^{-3} m^2/s. If the ANTEX file lacks receiver antenna PCO and PCV corrections for BDS or Galileo, the GPS values are used as a substitute. In addition, if the third frequency PCO and PCV corrections are absent in the ANTEX file, one can instead use the values from the adjacent frequency (Li et al. 2020b).

When completing all processing steps, PPPLib provides a simple but unified result file format containing the positioning information, receiver clock and ISB parameters, satellite elevation and azimuth angles, pseudorange and carrier phase post-fit residuals, tropospheric and ionospheric delay, as well as ambiguity information for each epoch. To evaluate the epoch-by-epoch variations of estimated parameters and their statistics, a visualization tool is provided to produce several plots, such as positioning error, satellite number, and dilution of precision.

Comparison of GNSS combination

In order to test and validate the PPPLib software, the performance of the dual-frequency ionospheric-free (DF-IF) PPP model is evaluated using a six-day period from December 1 to 6, 2019, from 17 MGEX observation stations, and the distribution is shown in Fig. 3. The full set of test results for other PPP models is shown in the User Manual, such as dual-frequency uncombined PPP or triple-frequency PPP models. The selected observation stations are equipped with

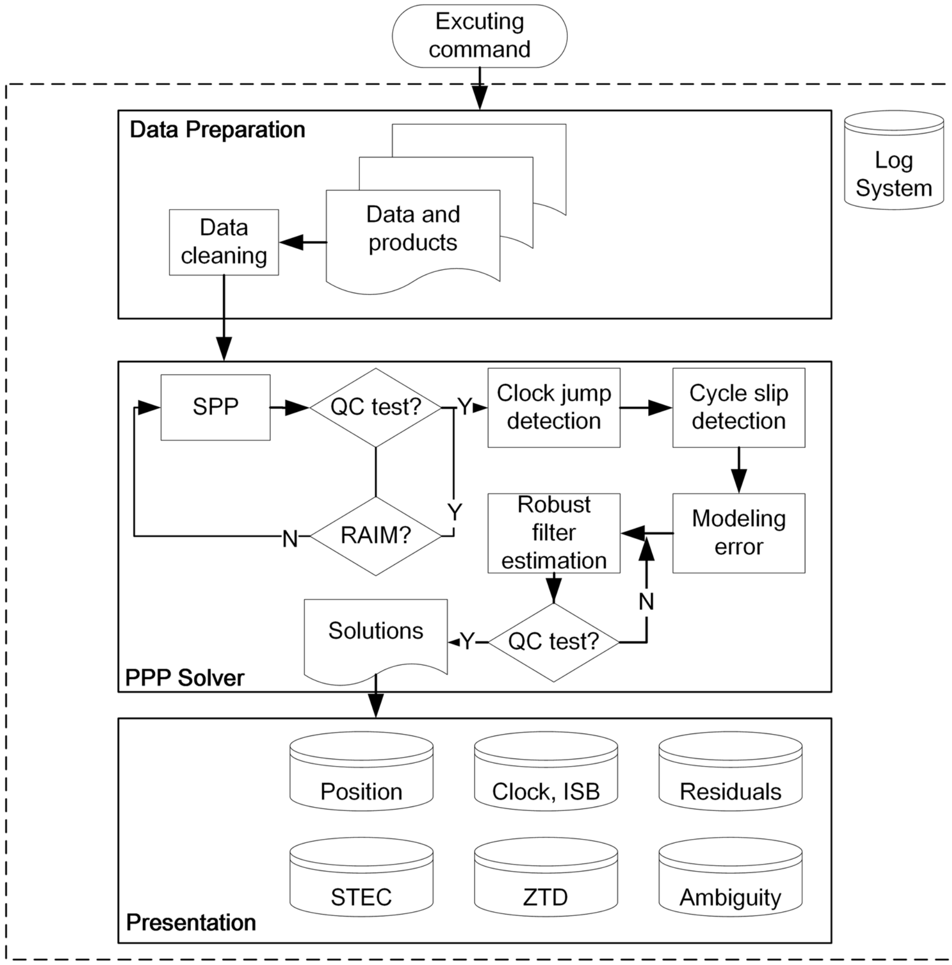

Fig. 2 GNSS-PPP data processing procedure in PPPLib. The software includes three main modules: data preparation module, PPP solver module, and the presentation module. (SPP: single point positioning, QC: quality control, RAIM: receiver autonomous integrity monitoring, ISB: inter-system bias, ZTD: zenith tropospheric delay, STEC: slant total electron content)

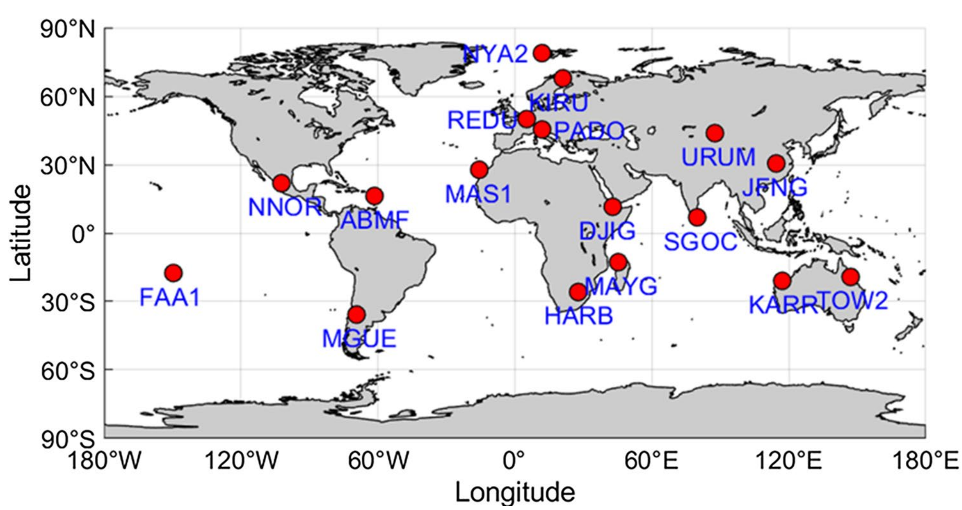

Fig. 3 Distribution of the user stations for investigating the performance of PPPLib software

multi-GNSS receivers capable of accepting multi-GNSS observation data. The sampling interval of the observations is 30 s. We use the abbreviations "G," "C," "E," "R," and "J" instead of GPS, Beidou, Galileo, GLONASS, and QZSS for convenient short expressions.

The "WUM" precise satellite orbit and clock products from the Wuhan university MGEX analysis center were used (Guo et al. 2015). The elevation cutoff angle was set to 7 degrees and the antenna calibration data are obtained from the igs14_2097.atx file. G-only, G + C,

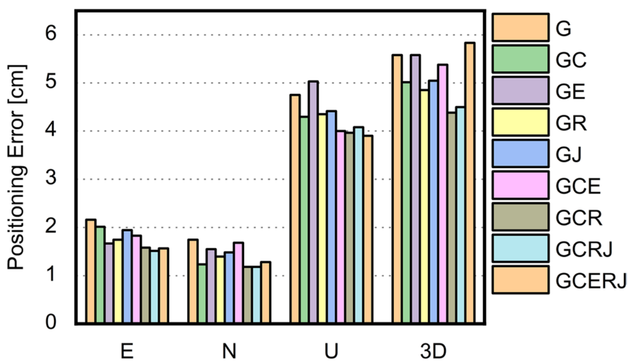

Fig. 4 Average RMS (cm) of positioning error derived from DF-IF PPP model with kinematic mode (G: GPS, C: BeiDou, E: Galileo, R: GLONASS, J: QZSS)

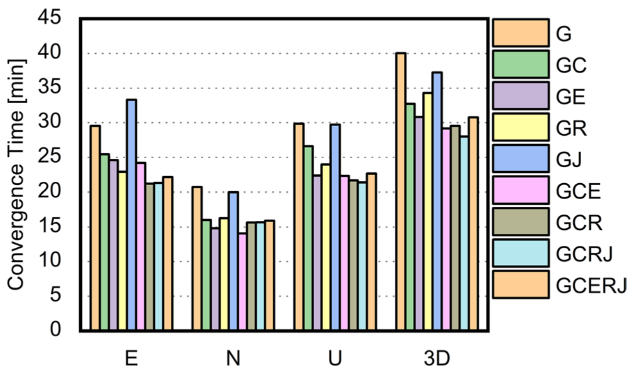

Fig. 5 Average convergence time (min) derived from DF-IF PPP model with kinematic mode (G: GPS, C: BeiDou, E: Galileo, R: GLONASS, J: QZSS)

G + E, G + R, G + C + E, G + C + R, G + C + R + J, as well as G + C + E + R + J combinations using DF-IF PPP models are performed and compared. Not only the positioning accuracy but also the convergence time is analyzed and presented. In this study, the reference positions are obtained from the IGS weekly SINEX file and used to assess positioning performance. The "convergence" is defined as obtaining positioning error in east, north, up or 3D direction less than the predefined threshold at the current epoch and the following 20 epochs (Li and Zhang 2014; Zhou et al. 2018). The predefined dual-frequency threshold was taken as one decimeter (Lou et al. 2015).

To access the contribution of multi-GNSS combinations to PPP solution, we perform contrast experiments using dual-frequency ionospheric-free PPP models in kinematic mode with G-only, G + C, G + E, G + R, G + J, G + C + E, G + C + R, G + C + R + J, and G + B + E + R + J combination schemes. The comparison results of positioning accuracy and convergence time in E, N, U, and 3D direction for the different schemes are shown in Figs. 4, 5 and Table 1 Overall, the multi-GNSS kinematic PPP has shown the accuracy of better than 2 cm in horizontal and 5 cm in the vertical components at the 68% level, while the positioning accuracy after convergence has shown no significant improvement compared to G-only scheme, which agreed with the results of Lou et al. (2015). The combined PPP has also shown a convergence improvement over the G-only scheme. The multi-GNSS PPP median convergence time can be reduced to less than 25, 16, 25, and 35 min in the east, north, up, and 3D directions, respectively. It is clearly noticeable that combined systems enhance the PPP solution with regard to positioning accuracy and convergence time. However, it is worth mentioning that the weighting of different GNSS measurements needs to be correctly handled. Otherwise, the non-proper weighting will lead to worse performance, which can be observed from Fig. 4 in G + C + E + R + J scheme. Based on this insight, an adaptive and robust Helmert variance component estimation a-posteriori weighting will be employed in the next version of the software to resolve this problem (Chang et al. 2018; Li et al. 2020a; Yang et al. 2001, 2005).

Table 1 RMS of positioning errors (cm) and convergence time (min) using DF-IF PPP models with different GNSS system combinations in east, north, up, and 3D direction, respectively

	Positioning Errors				Convergence Time			
	East	North	Up	3D	East	North	Up	3D
G	2.17	1.18	4.75	5.58	29.5	20.7	29.9	40.3
GC	2.02	1.23	4.30	5.02	25.4	16.0	26.6	32.7
GE	1.67	1.55	5.03	5.58	24.6	14.8	22.4	30.8
GR	1.75	1.40	4.35	4.85	22.9	16.3	24.0	34.3
GJ	1.95	1.48	4.41	5.05	33.3	20.0	29.7	37.3
GCE	1.83	1.68	4.00	5.38	24.2	14.1	22.3	29.2
GCR	1.58	1.18	3.97	4.38	21.2	15.6	21.7	29.5
GCRJ	1.52	1.18	4.08	4.50	21.3	15.7	21.4	28.0
GCERJ	1.57	1.28	3.90	4.43	22.1	15.9	22.6	30.7

Summary and conclusions

We have proposed a software package named PPPLib, for computing the PPP solutions using different GNSS constellations. The software can be operated in ionospheric-free or uncombined mode, using single-, dual-, or triple-signal combinations effectively. 24 h observation data sets obtained from 17 MGEX stations during 6 days were processed to validate and assess the performance of PPPLib. The results indicate that PPPLib is able to provide centimeter-level PPP solutions for dual-frequency in kinematic mode. It was concluded that the integration of multi-GNSS can enhance the PPP solution. The combined PPP has shown a significant convergence improvement over the GPS-only PPP, while the positioning accuracy after convergence has no shown significant improvement. Meanwhile, weighting the measurements from different GNSS should be properly handled. Otherwise, the non-proper weighting will lead to worse multi-GNSS PPP performance.

PPPLib provides an important possibility to benefit from the potential advantages of multi-constellation and multi-frequency. The C/C++ source code, and the User Manual for PPPLib, can be found on the GPS Toolbox Web site at https://geodesy.noaa.gov/gps-toolbox/. The software is continuing to evolve, future features of PPPLib will be as follows:

- GNSS/INS tightly coupled (under testing)
- PPP ambiguity resolution (under testing)
- Robust processing strategy for the real kinematic scene
- Enhanced algorithms for GNSS/INS coupled

Some bugs may exist in PPPLib and the software contents will continue to be improved for further applications. Comments and suggestions from users are welcome to send to the first author.

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Data Availability All data and material supporting the conclusions of this article are available. They are either deposited in publicly available repositories or presented in the related paper.

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