**FiPPP**: **Open-source software for multi-GNSS precise point positioning from single- to five-frequency observations**

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**Abstract** An open-source software package, Multi-GNSS Five-frequency Precise Point Positioning (FiPPP), has been developed to perform system- and frequency-wide precise point positioning (PPP) from single- to five-frequency observations of GPS, BeiDou, and Galileo. The new software is implemented in the C++ language and executes on the Windows operating system. FiPPP is designed to make full use of the received multi-frequency and multi-GNSS observations according to the flexible ionospheric-free combination and uncombined strategy. In addition to positioning, widely used products such as multi-frequency differential code bias and code observation-specific signal bias can also be estimated. The tropospheric delays, ambiguity parameters, and bias information are synchronously output with the PPP estimation. The performance of static PPP has been assessed, with respect to positioning accuracy and convergence time, using four ionospheric-free and uncombined experimental tests. The results indicate that centimeter-level positioning accuracy can be obtained by FiPPP.

**Keywords** Open-source software; Five frequencies; Precise Point Positioning; Ionospheric-free combination; Uncombined mode

# Introduction

Global navigation satellite systems (GNSSs), with all-weather high-precision positioning, navigation, and timing (PNT) capabilities, are being integrated into the application field of new infrastructure (Hein 2020, Yang et al. 2021, Li et al. 2022). To improve the performance of GNSS PNT services, all major navigation systems are continuously updated with respect to satellite geometry structure, constellation configuration, augmentation information, and signal modulation (Montenbruck et al. 2017, Cai et al. 2021, Yang et al. 2022). For instance, the BeiDou system with global coverage (BDS-3) is synchronously modulated with five-frequency signals (B1I, B3I, B1C, B2a, and B2); GPS can provide location-based services with L1 C/A, L1C, L2C, and L5 signals; Galileo constantly reduces the signal-in-space ranging error of five-frequency observations (E1, E5a, E5b, E5, and E6); and the new-generation GLONASS-K2 satellite changes to code division multiple access mode with three-frequency civil signals (Steigenberger et al. 2017, Zhang et al. 2020, Li et al. 2022). It has been suggested that the advent of multi-GNSS and multi-frequency observations provide a great opportunity to reduce the convergence time and improve the positioning accuracy of precise point positioning (PPP) by exploiting the abundance of observations (Nie et al. 2020, Li et al. 2020). However, because of the limitations of the GNSS data processing model, the system- and frequency-wide observations and the multi-GNSS and multi-frequency observations have not been fully used and integrated into PPP (Geng et al. 2020, Wang et al. 2022a).

The optimal linear combination of different observations is the prerequisite for multi-frequency integration (Li et al. 2010, Wu et al. 2022a, Hu et al. 2023). Although multi-GNSS observations from single- to triple-frequency signals have been widely studied, there are three main problems with GNSS PPP that have still not been completely solved. First, the benefits of single- to five-frequency multi-GNSS observations have not been fully analyzed or achieved (Chen et al. 2021, Jin et al. 2020). Second, each GNSS system usually uses the fixed combination model, such as the traditional dual-frequency ionospheric-free (IF) combination (Zumberge et al. 1997), in which the additional frequencies are commonly ignored. Third, because the types and versions of GNSS receivers are usually not identical for each station, the performance of decoding multi-GNSS observations needs to be considered in the solution of PPP (Liu et al. 2019, Nie et al. 2020). To satisfy the requirements of single- to five-frequency multi-GNSS applications and provide a platform to solve system- and frequency-wide PPP, a preliminary version of the open-source FiPPP software has been developed. According to the optimal combination strategies (Yu 2011, Zhang et al. 2020, Hu et al. 2023), either the IF combination or the uncombined (UC) mode can be selected and set in the configuration files. It should be noted that the bias parameters should be carefully defined and eliminated during the construction of a multi-GNSS and multi-frequency PPP model (Pan et al. 2018). For this purpose, bias products, such as differential code bias (DCB) and observation-specific signal bias (OSB), can be used and estimated by FiPPP to correct the observations.

Several multi-GNSS PPP software packages have been reported, which are publicly accessible in the GNSS community; for example, RTKLIB (Takasu et al. 2009), goGPS (Herrera et al. 2016), PPPLib (Chen et al. 2021), and GAMP (Zhou et al. 2018). However, the flexible combination of the whole set of received observations is not considered in the abovementioned software packages, which only perform single- to triple-frequency PPP. In addition to the GNSS system- and frequency-wide PPP service, FiPPP can also present results through a visual interface, including formatted results files, station distributions, counting convergence time and positioning accuracy, and the positioning residuals series. To aid in debugging and understanding the software, all code is commented, and the mathematical model of the multi-GNSS and multi-frequency combination is presented in the user manual. The open-source FiPPP code, including several examples for testing, can be downloaded from the GPS Toolbox website at <https://geodesy.noaa.gov/gps-toolbox/>.

The features of FiPPP are outlined and the performance of multi-GNSS PPP from single- to five-frequency observations with the IF combination and UC mode is assessed. First, a brief introduction to the FiPPP software is presented. Second, the PPP processing and its performances are described. Finally, the contributions of FiPPP are summarized, and the modules to be further developed are discussed.

# FiPPP software features

The FiPPP software implements the sequential least squares filtering algorithm, and uses the postprocessing strategy to estimate the unknown parameters. The software was developed in the C++ language and executes on the Windows operating system. FiPPP uses CMAKE to manage the PPP project, and requires the Eigen library to be installed to perform the matrix operations. Meanwhile, it is recommended that user selects the GCC and CLion IDE for GNU compiler, and the Visual Studio 2022 Community IDE for VS compiler. Details of installing, debugging, compiling, and executing the software are presented in the user manual. The structure of FiPPP software is illustrated in Fig. 1, and the main features of the software are listed below:

* Supports a single- to five-frequency UC PPP solution.
* Supports GPS, BDS-3, Galileo, and a combination of them.
* Performs multi-frequency and multi-GNSS single-point positioning (SPP).
* Performs multi-GNSS dual- to five-frequency IF-combined PPP.
* Performs system-wide and frequency-wide integrated GNSS PPP.
* Performs multi-GNSS and multi-frequency kinematic PPP (in development).
* Supports the selection of frequencies, such as the BDS-3 IF combination with B1C/B2a+B1C/B2+B1I/B3I or B1C/B2a/B2+B1I/B3I.
* Corrects GNSS observations by the issued DCB, OSB, and inter-frequency clock bias (IFCB) products.
* Estimates GPS third frequency IFCB parameters.
* Performs multi-frequency DCB and code OSB estimation and provides its formatted output.
* Supports UPD/IRC single-difference dual-frequency IF-combined PPP-AR (in development).
* Supports visualization with a debug log and visual interface.

**Fig1**

**Fig**. **1** Main features of FiPPP software

The main purpose of the FiPPP is to perform multi-frequency and multi-GNSS PPP by the flexible IF combination and UC mode with the observations from one to five frequencies. SPP is solved first to provide the approximate coordinates for PPP. In addition, the multi-frequency DCB and code OSB parameters can be estimated. The main functions of the FiPPP and its processing methods are illustrated in Fig. 2.

**Fig2**

**Fig. 2** Main steps of data processing procedure in FiPPP software

The procedure executed by FiPPP can be divided into two parts, namely DCB and OSB estimation and PPP solution. Before running the software, the observations, precise satellite products, and related files (such as precise clock offsets, orbit, and ERP) should be prepared. To clean the multi-GNSS and multi-frequency observations, observation quality control (QC) algorithms, such as cycle slip and gross error detection (Blewitt 1990, Hu et al. 2018), are applied. In addition, the IF combination or UC mode can be selected to construct the observation functions. Therefore, the optimal combination coefficients of multi-frequency observations are estimated (Hu et al. 2023, Zhang et al. 2020). All received multi-GNSS observations are fully used in the PPP; alternatively, the signals used can be chosen by the user. It should be noted that the multi-frequency DCB and code OSB can be synchronously estimated from the global stations, which can also be used to correct the PPP observations. Furthermore, modeling errors, including tropospheric zenith delay (ZTD), ionospheric delay, inter-system bias (ISB), and IFCB, are approximatively corrected by precise products and estimated as unknown parameters (Wang et al. 2022a), where the multi-frequency bias parameters should be derived from the traditional dual-frequency mode.

Similarly to other open-source PPP software, the station coordinates are set to constant values in the static mode, whereas white noise is introduced in the kinematics mode (Chen et al. 2021). However, because of the lack of a residual test algorithm, some kinematic PPP results fail to converge; a solution to this problem is still being developed. White noise is used in the estimation of the receiver clock, and random-walk noise is used for ZTD and the bias parameters. In addition, the PCO and PCV corrections from the ANTEX file are applied, and the values of GPS are employed to replace other GNSS system as the lack of antenna information. To overcome the loss of multi-frequency PCO and PCV, the values of the adjacent frequencies can be assigned (Chen et al. 2021). More details concerning the configuration of FiPPP can be found in the user manual. Furthermore, partial ambiguity resolution is also implemented. After the execution of FiPPP, the results and log files, including positions, residuals, ZTD, DCB, OSB, ambiguity, and other files, are produced in a widely used format. FiPPP provides some useful tools, such as the visualization of PDOP, residuals, and analysis of convergence time.

# Positioning results of FiPPP software

To test the performance of the FiPPP software, 20 MGEX global stations with multi-GNSS and multi-frequency observations were selected, as shown in Fig. 3. The experimental time was September 9, 2022, and stations with BDS-3 five-frequency observations were used. Four groups of experimental tests were designed to assess the performance of static PPP with respect to positioning accuracy and convergence time.

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**Fig. 3** Distribution of 20 MGEX stations selected for using in PPP experiments

First, because of the ability to perform single- to five-frequency PPP, the advantages of multi-frequency observations were tested, as follows.

Test 1: The five-frequency observations of BDS-3 were used to test the performance of the FiPPP software, by performing single- to five-frequency positioning with the IF combination and UC mode, separately. The positioning accuracy and corresponding convergence time of BDS-3 single- to five-frequency static PPP are presented in Fig. 4. The figure shows that similar centimeter-level positioning accuracy could be obtained in most of the experiments, which indirectly verifies the validity and reliability of FiPPP. As the number of frequencies used increased, the positioning accuracy improved but the convergence time became slightly worse because of the function noise amplification with multi-frequency observations, particularly in the E direction. This will be solved in future by the partial PPP-AR algorithm.

**Fig4.1**

**Fig4.2**

**Fig. 4** Average positioning accuracy and convergence time of BDS-3 single- to five-frequency static PPP with the IF combination (top) and UC mode (bottom)

Test 2: In addition to multi-frequency positioning, the benefits of multi-GNSS observation were also verified. Nine combinations of different systems were evaluated: G (GPS-only), G+E (GPS+Galileo), and G+C+E (GPS+BDS+Galileo) with single-, double-, and triple-frequency observations. Similarly, the IF combination and UC mode of PPP were evaluated, using two forms of triple-frequency IF, namely IF123 and IF1213. Table 1 and Fig. 5 summarize the average positioning residuals and convergence times in the E, N, and U directions. The results presented in Table 1 and Fig. 5 suggest that increasing the number of GNSS systems can reduce the positioning error and convergence time. However, in some cases, the PPP performance is slightly worse than that of a GPS-only solution, particularly for IF combinations, in which the ISB and receiver clock parameters should be redefined.

**Table 1** Average positioning accuracy and convergence time of multi-GNSS PPP from single- to five-frequency observations based on the IF combination and UC mode

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| PPP strategies | Positioning Accuracy(cm) | | | Convergence Time (min) | | |
| E | N | U | E | N | U |
| UC1-G | 4.136 | 2.399 | 7.192 | 112.600 | 56.300 | 92.650 |
| UC12-G | 1.195 | 0.446 | 1.713 | 50.238 | 37.976 | 43.667 |
| UC123-G | 1.181 | 0.469 | 1.824 | 60.810 | 42.714 | 51.214 |
| UC1-GE | 3.281 | 1.984 | 7.244 | 94.750 | 47.000 | 84.125 |
| UC12-GE | 1.035 | 0.491 | 3.173 | 29.214 | 33.286 | 40.690 |
| UC123-GE | 1.027 | 0.493 | 3.217 | 31.857 | 37.571 | 44.667 |
| UC1-GEC | 3.661 | 1.900 | 8.569 | 119.625 | 54.438 | 120.563 |
| UC12-GEC | 1.416 | 0.464 | 3.943 | 26.600 | 16.700 | 28.050 |
| UC123-GEC | 0.950 | 0.472 | 3.384 | 27.722 | 29.722 | 37.361 |
| IF12-G | 1.199 | 0.451 | 1.805 | 49.048 | 26.452 | 37.310 |
| IF123-G | 2.431 | 0.741 | 2.345 | 205.559 | 128.912 | 123.412 |
| IF1213-G | 1.517 | 0.600 | 2.104 | 58.476 | 35.595 | 43.238 |
| IF12-GE | 0.975 | 0.486 | 2.587 | 31.833 | 24.238 | 32.786 |
| IF123-GE | 2.475 | 4.253 | 12.013 | 68.421 | 62.316 | 61.053 |
| IF1213-GE | 1.972 | 3.336 | 7.299 | 33.762 | 30.190 | 50.952 |
| IF12-GEC | 0.843 | 0.486 | 2.948 | 22.972 | 26.611 | 25.639 |
| IF123-GEC | 2.371 | 2.838 | 10.882 | 71.967 | 45.500 | 41.867 |
| IF1213-GEC | 1.895 | 2.947 | 6.555 | 27.306 | 27.833 | 43.722 |

**Fig5.1**

**Fig5.2**

**Fig. 5** Average positioning accuracy and convergence time of multi-GNSS PPP with G, G+E, and G+C+E from single- to triple-frequency observations based on the IF combination (top) and UC mode (bottom)

Second, compared with the traditional multi-GNSS and multi-frequency PPP solutions, the FiPPP software can make full use of the received observations. The PPP performance of system- and frequency-wide observations was tested as follows.

Test 3: The traditional dual-frequency GNSS PPP was evaluated using GPS, Galileo, and BDS-3 observations, where the B1I+B3I frequencies were used in BDS-3. Additionally, the received observations were tested from single- to five-frequency PPP using the IF combination and UC mode. The PPP results of positioning accuracy and convergence time are shown in Fig. 6. The figure indicates that results similar to those of multi-frequency UC modes could be obtained as the number of signals used increased. However, for the centimeter-level results of IF combinations, the use of all received observations could not significantly improve the PPP performance. The algorithms for PPP-AR and QC test, and their optimal combination, will be further studied in future to improve on the current version.

**Fig6.1**

**Fig6.2**

**Fig. 6** Positioning accuracy and convergence time of system- and frequency-wide GNSS PPP from single- to five-frequency observations of the IF combination (top) and UC mode (bottom)

Third, the multi-GNSS and multi-frequency DCB and code OSB can also be solved in the FiPPP software. The DCB products of CAS center (Wang et al. 2022b) were taken as references to analyze the DCB accuracy of FiPPP, and the OSB products of WHU center were used to evaluate the code OSB accuracy. To show the accuracy of the estimated DCB and OSB, Fig. 7 plots the average residuals of all satellites. The figure shows that the DCB parameters are highly consistent with those of the publicly available products, whereas some of the OSB values deviate from the normal values. The constraint of OSB estimation will be further tested in future to increase the consistency of multi-frequency OSB. Moreover, because of the existence of bias parameters, the multi-frequency and multi-GNSS PPP solutions are typically impacted by them (Chen et al. 2022, Li et al. 2023). In the FiPPP software, the bias parameters are carefully defined and categorized as unknown variables, although the publicly used multi-frequency bias products, such as DCB, OSB, and IFCB, can be used instead. Therefore, the performance of PPP using precise products was compared with that using estimation, as follows.

Test 4: To assess the model of bias processing, two methods for bias correction in FiPPP were compared, namely estimation and precise products. The results of dual- and five-frequency GNSS PPP are shown in Fig. 8, in which EST denotes the estimation strategy for the five-frequency PPP solution. These results show that the EST strategy could reduce the positioning error and convergence time compared with the use of precise products for five-frequency IF and UC PPP. However, similar performance could be obtained with dual-frequency and five-frequency PPP, which means that some unmodeled errors in multi-frequency functions should be further processed. The FiPPP software provides a useful tool for conducting system- and frequency-wide studies.

**Fig7**

**Fig. 7** Average DCB and code OSB residuals for different GNSS systems

**Fig8**

**Fig. 8** Positioning accuracy and convergence time of PPP solution using different bias correction methods

# Summary and prospects

The multi-GNSS and multi-frequency PPP solution is widely used in the GNSS community. A system- and frequency-wide GNSS PPP software package, named FiPPP, was developed to perform both IF and UC solutions from single- to five-frequency observations. In addition, flexible IF combinations of up to five frequencies from different GNSS systems can be selected, to consider all received observations. Finally, the multi-GNSS and multi-frequency DCB and code OSB can be estimated to correct the biases in PPP.

From four experimental tests of static PPP experiments with 20 global stations, it was found that centimeter-level positioning accuracy could be obtained using the FiPPP software. In most cases, by considering all received observations, FiPPP was able to optimize the PPP performance with respect to positioning accuracy and convergence time. However, in some cases, the PPP performance was similar to, or slightly worse than, that achieved with the traditional dual-frequency strategy. Because of unmodeled errors, it is necessary to continuously improve the positioning model, defined bias, and constraint condition. Nevertheless, FiPPP provides a useful open-source platform for conducting system- and frequency-wide PPP research for the GNSS community. The source code, examples, and user manual of the FiPPP software are available from the GPS Toolbox website.

To address the insignificant improvement in positioning performance resulting from the introduction of multi-GNSS and multi-frequency observations, we propose further work on the development of FiPPP, including the following:

* Testing and editing of residuals, and robust estimation.
* Estimation of multi-frequency phase OSB parameters.
* Resolution of multi-frequency partial ambiguity.
* Solution of real-time kinematic multi-GNSS PPP.
* Adjustment of optimal constraint of parameters.

Instructions for compiling and running the FiPPP software, and more details of the software, can be found in the user manual. Inevitably, bugs and inaccurate configurations may occur as the changes of inputting observations.

Declarations

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**Availability of data and materials** The data used to support the findings of this study are available from the corresponding author upon request.

**Authors’ contributions** Chao Hu wrote the main manuscript and user manual; Chao Hu and Ruiguang Wang developed the FiPPP software. All authors reviewed the manuscript and tested the examples.

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**Competing interests** The authors declare no competing interests.

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**Consent for publication** Not applicable.

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