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GPS TOOLBOX

GINav: a MATLAB-based software for the data processing and analysis of a GNSS/INS integrated navigation system

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Abstract
With the development of GNSS, many open-source software packages have become available for GNSS data processing. However, there are only a handful of open-source software that can handle GNSS/INS integrated data, even though GNSS/INS integration schemes have been widely used in vehicle navigation systems due to their high accuracy, stability, and continuity in harsh environments. Considering the above, we developed an open-source software, GINav, which focuses on the data processing and analysis of a GNSS/INS integrated navigation system. GINav is suitable for in-vehicle situations and aims to provide a useful tool for carrying out GNSS/INS-related research. It is a convenient platform for testing new algorithms and experimental functionalities. GINav is developed in the MATLAB environment. It provides a user-friendly graphical user interface (GUI) to facilitate learning how to use it quickly. A visualization tool, GINavPlot, is provided for solution presentation and error analysis. We have conducted experimental tests to validate and assess the performance of GINav. The results indicate that GINav can provide navigation solutions comparable to general GNSS/INS accuracy standards, and it can handle both suburban and urban GNSS/INS integrated datasets.

Keywords GNSS/INS integration · GNSS · Open-source · Ginav · MATLAB

Introduction

Global Navigation Satellite Systems (GNSS) have been widely used to provide high-accuracy PVT (position, velocity and time) service for users. Alongside this rapid development of GNSS, multi-GNSS and multi-frequency real-time kinematic (RTK) and precise point positioning (PPP) technologies have been widely researched to provide high-accuracy positioning. For RTK, Geng and Bock (2013) and Li et al. (2013) have demonstrated that the additional frequency signals speed up the carrier-phase ambiguity resolution and improve positioning accuracy and reliability. For PPP, Chen and Chang (2020) have verified that multi-constellation and multi-frequency can improve positioning accuracy and shorten PPP convergence time. However, although positioning of GNSS performs works well in practical applications, GNSS signals are prone to frequent interruption or even disappearance in an urban canyon, tunnel, and or similar environment, which brings great challenges to continuous high-accuracy positioning. Compared to using GNSS only, a GNSS/inertial navigation system (INS) integrated navigation system may be an ideal choice to provide long-term high-accuracy positioning. Its advantage is that pure INS can provide acceptable navigation accuracy over short time spans, even in the case of GNSS signal interruption. GNSS/INS integration has become an indispensable part of vehicle navigation systems in recent years, and research has been dedicated to GNSS/INS integrated navigation systems and

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has achieved fruitful results. For example, Han and Wang (2012) have developed a dual-rate filter to integrate time-differenced carrier phases and pseudoranges with INS measurements. Li et al. (2017a) have demonstrated that the tightly coupled integration of multi-GNSS single-frequency RTK and low-cost inertial measurement unit (IMU) can enhance positioning accuracy, continuity, and reliability.

With the development of GNSS, open-source software such as RTKLIB (Takasu and Yasuda 2009), goGPS (Realini and Reguzzoni 2013), GAMP (Zhou et al. 2018), PPPLib (Chen and Chang 2020), have been developed for GNSS data processing and analysis. However, only a few open-source projects have implemented GNSS/INS integration algorithms preliminarily, and most of them focus on GNSS data processing. Taking all of the above into account, it could be argued that there is a demand for open-source software that has in-depth research on the processing of GNSS/INS integrated data and can provide a convenient platform to test GNSS/INS-related algorithms. To meet such a demand, we have developed the convenient and powerful GINav software package, which focuses on the research and development of GNSS/INS integration algorithms. GINav supports almost all the usual GNSS/INS integration modes. It refers to many excellent GNSS post-processing software, such as RTKLIB and PPPLib, and makes some improvements. Compared with many open-source GNSS data processing software, the advantage of GINav mainly lies in the research of GNSS/INS integration algorithms. It has a clear algorithm structure and a lot of comments, which are very helpful for users to learn it quickly. In terms of integrity, it does not provide status tracking files like other software. Instead, it directly prints some useful information, warnings, and errors in the command window, so that users can find problems in a timely manner. Additionally, GINav also supports the usual GNSS positioning mode for multi-constellation and multi-frequency GNSS data processing.

A brief description of the GINav is given first. Afterward, the experimental results are presented, which validate and assess the performance of GINav. Finally, the main conclusions are summarized in the last section.

GINav software

GINav is a data post-processing software developed in the MATLAB environment. Fundamentally, GINav aims to be a useful tool for carrying out GNSS/INS-related research. It provides a useful GUI for configuring input files and automatically matches the required files by specifying the configuration file. Details of the configuration file and instructions on installing and running GINav can be found in the user manual. Furthermore, GINav uses the LAMBDA v3.0 toolbox of Curtin University to resolve the carrier phase ambiguities (Verhagen et al. 2012). If you use post-processing kinematic (PPK), post-processing static (PPS), or PPK/INS mode to process data, please download and install the lambda-3.0.zip file from http://gnss.curtin.edu.au/research/lambda.cfm. The main features of the GINav software include the following:

- Support of GNSS/INS loosely coupled (LC) modes, which includes standard single positioning (SPP)/INS LC, post-processing differenced (PPD)/INS LC, PPK/INS LC, and PPP/INS LC
- Support of GNSS/INS tightly coupled (TC) modes, including SPP/INS TC, PPD/INS TC, PPK/INS TC, and PPP/INS TC
- INS-aided cycle slip detection and robust estimation for GNSS/INS integration
- Support pf multi-constellation and multi-frequency GNSS data processing
- Support of GNSS absolute positioning modes, including SPP and PPP
- Support of GNSS relative positioning modes, including PPD, PPK, and PPS
- Convenient visualization

To allow the reader to become better familiar with GINav, Fig. 1 shows a flowchart of data processing and analysis. The data processing starts with the data reading and adjustment. GINav first reads all the required files and makes some adjustments to the data, which makes GINav more efficient. The user can also specify the order in which BDS-2 and BDS-3 observation frequencies are to be used. The GNSS or GNSS/INS processors (depending on the user's choice) are then executed to generate navigation solutions. In the GNSS processor, the SPP solution is used as a predicted value for the filtering process of the other positioning modes, which means the SPP is a crucial step. In SPP mode, the Receiver Autonomous Integrity Monitoring (Kaplan and Hegarty 2006) algorithm and quality control tests are used to exclude abnormal satellites and check the quality of solutions. However, in some GNSS-challenged environments, the quality of solutions given by SPP is still not satisfactory, so we implemented enhancement algorithms to avoid unreliable results. Moreover, in the PPK, PPS and PPP mode, the cycle slip (CS) detection 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 should be reinitialized. In any GNSS/INS processor, the information provided by GNSS can be used to correct the navigation solution of the INS component. Meanwhile, the information predicted by INS can aid GNSS in detecting abnormal observations contaminated by a CS or gross error. In order to avoid the influence of outliers on the navigation system, a robust Kalman filter

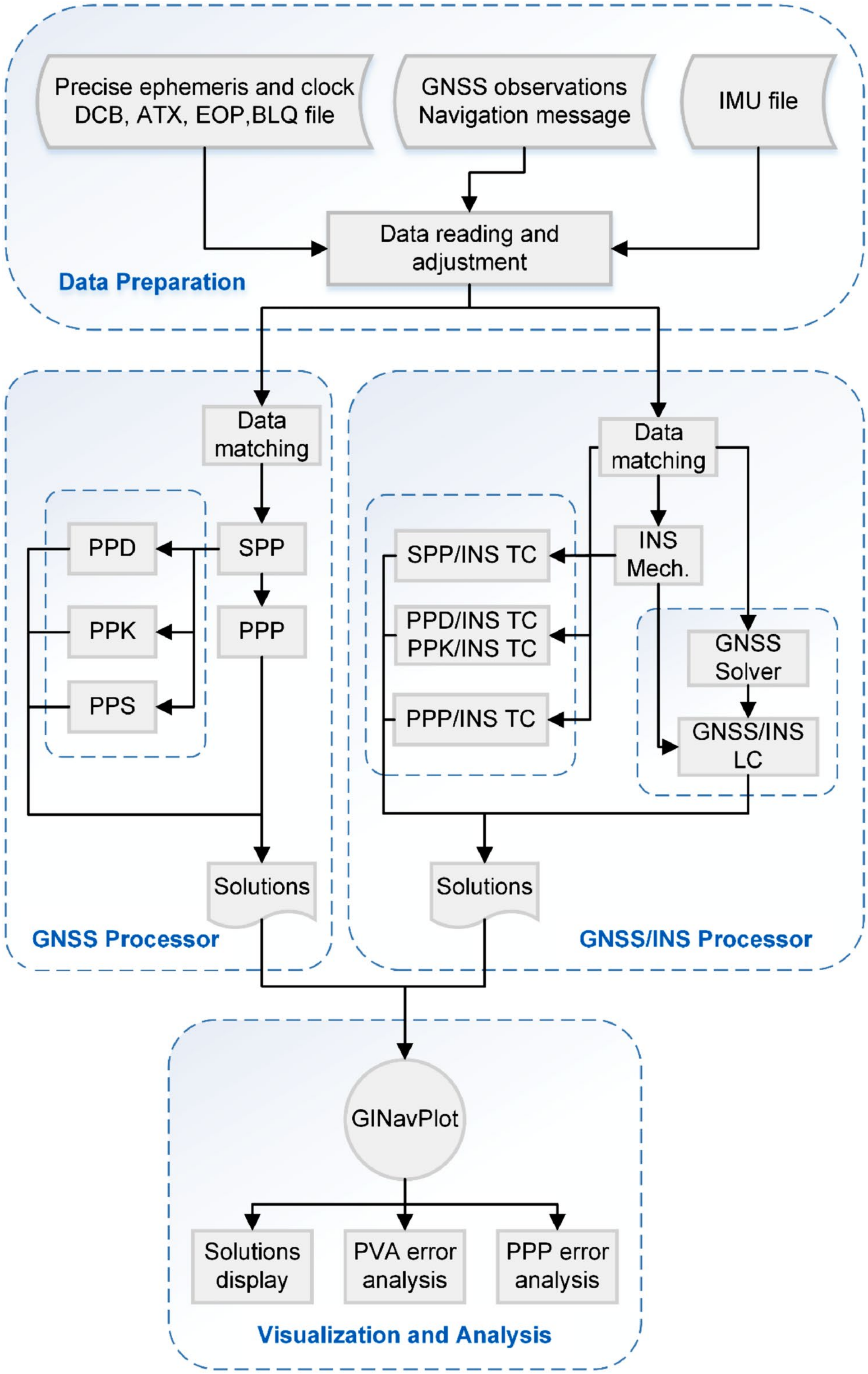

Fig. 1 Data processing and analysis procedure in GINav. The software includes four main modules: data preparation module, GNSS processor module, GNSS/INS processor module, and visualization and analysis module (INS Mech: INS mechanization; PVA: position, velocity and attitude)

based on the IGG-III model (Yang 1991; Yang et al. 2002) is employed in the GNSS/INS processor, and some INS-aided CS detection methods (Kim et al. 2015; Takasu and Yasuda 2008) are implemented in PPK/INS TC and PPP/INS TC modes. Finally, GINav provides a useful graphical tool, GINavPlot, to plot and analyze the solutions. GINavPlot can display some basic information, such as motion trajectories and the number of satellites, as well as analyze position, velocity and attitude errors when reference truth is available.

Experimental results and analysis

To validate and evaluate the performance of GINav software, two experimental tests were conducted, and the results are presented in this section. Test one used a suburban vehicle dataset to evaluate the performance of GNSS/INS integration modes provided by GINav, while test two used an urban vehicle dataset to assess the availability of GINav and the practicality of a GNSS/INS integrated navigation system.

Test one

The suburban vehicle dataset was collected at the China University of Mining and Technology on March 28, 2019. During the experimental test, an integrated Trimble R10 receiver/antenna and the IMU of NovAtel SPAN-CPT were employed to collect GNSS and inertial data, respectively. Figure 2 shows the vehicle trajectory. In this test, data were processed with eight GNSS/INS integration modes, namely, (1) SPP/INS LC, (2) SPP/INS TC, (3) PPD/INS LC, (4) PPD/INS TC, (5) PPP/INS LC, (6) PPP/INS TC, (7) PPK/INS LC, and (8) PPK/INS TC. The reference solutions were obtained from the NovAtel Inertial Explorer 8.6 software in smoothed RTK/INS tightly coupled mode. The comparison results of navigation accuracy for the different modes are shown in Figs. 3, 4, and 5 and in Table 1. Overall, the position, velocity and attitude accuracy of the various GNSS/INS integration modes meets expectations. In terms of the integration mode, the navigation accuracies of the GNSS/INS LC and TC modes are comparable. However, Figs. 4 and 5 show that the velocity and attitude accuracies of the SPP/INS TC mode are significantly better than that of the SPP/INS LC mode. This happens because in the SPP/INS TC mode, besides pseudoranges, we also use Doppler observations in the measurement update of the filter. In terms

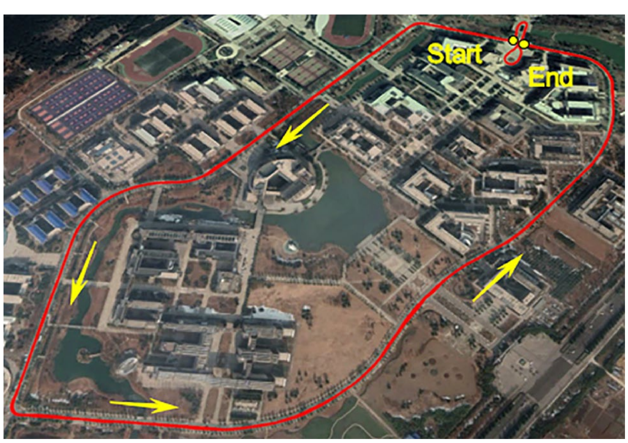

Fig. 2 Reference trajectory indication

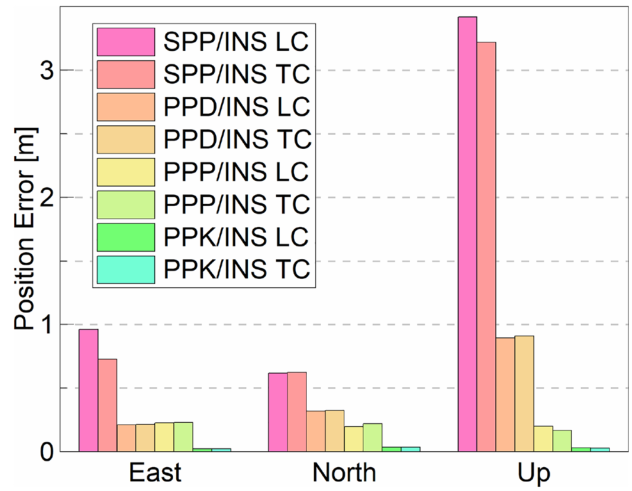

Fig. 3 Position error derived from the GNSS/INS integration modes provided by GINav

of positioning mode, Fig. 3 shows that the order of positioning accuracy from high to low is PPK/INS, PPP/INS, PPD/INS, and SPP/INS modes. As the statistical results in Table 1 show, the modes PPK/INS, PPP/INS, PPD/INS, and SPP/INS can achieve positioning accuracy at the centimeter, small sub-meter, large sub-meter, and meter level, respectively. This is comparable to general GNSS/INS accuracy results (Han and Wang 2012; Li et al. 2017bLi et al. 2017c).

Test two

The urban vehicle dataset was collected in a typical urban canyon of Tokyo on December 19, 2018. During the experimental test, a Trimble NETR9 receiver (with an unknown external antenna) and the Tamagawa-seiki TAG264 IMU

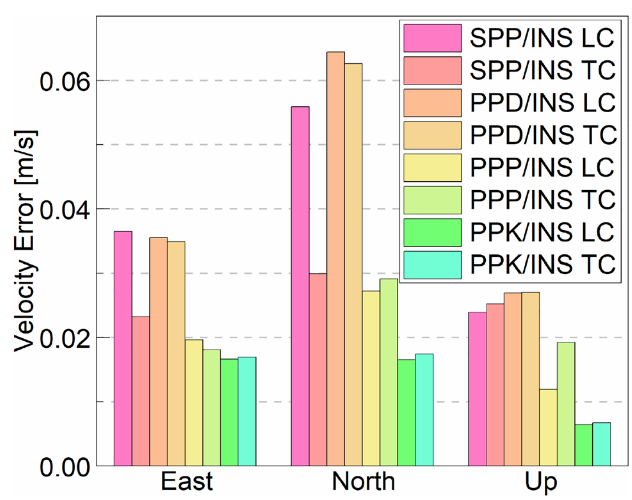

Fig. 4 Velocity error derived from the GNSS/INS integration modes provided by GINav

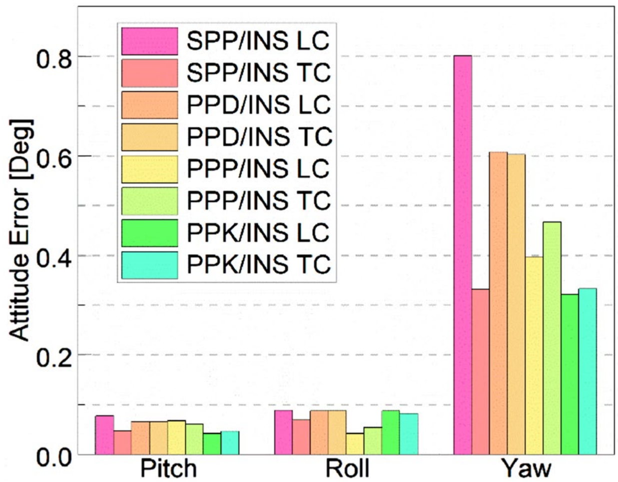

Fig. 5 Attitude error derived from the GNSS/INS integration modes provided by GINav

were employed to collect GNSS and inertial data, respectively. Due to the poor surrounding environment, the GNSS signals were frequently blocked by overpass or high-rise buildings, and the vehicle experienced frequent acceleration and deceleration. To assess the availability of GINav and the practicality of GNSS/INS integration mode in a harsh urban environment, three schemes are implemented in this test: (1) RTKLIB PPK, (2) GINav PPK, and (3) GINav PPK/INS TC. It should be stressed that all three schemes used the same configuration options, and the multi-GNSS included GPS, GLONASS, Galileo, BDS and QZSS; all were used due to the poor environment. Figure 6 shows the 2D vehicle trajectory of all three schemes. A, B, and C denote partial amplification areas where GNSS signals are almost completely obscured by the overpass and buildings. As shown in the figure, the PPK/INS TC mode was able to track the reference trajectory of the vehicle smoothly and provided continuous

Table 1 Summary of results: position, velocity and attitude RMS errors of the GNSS/INS integration modes provided by GINav

Mode	Position (m)			Velocity (m/s)			Attitude (°)		
	East	North	Up	East	North	Up	Pitch	Roll	Yaw
SPP/INS LC	0.960	0.617	3.418	0.036	0.056	0.024	0.078	0.089	0.802
SPP/INS TC	0.725	0.622	3.220	0.023	0.030	0.025	0.048	0.069	0.332
PPD/INS LC	0.210	0.319	0.892	0.036	0.064	0.027	0.066	0.088	0.608
PPD/INS TC	0.213	0.322	0.908	0.035	0.063	0.027	0.066	0.087	0.602
PPP/INS LC	0.226	0.196	0.198	0.019	0.027	0.012	0.068	0.042	0.398
PPP/INS TC	0.228	0.218	0.166	0.018	0.029	0.019	0.061	0.054	0.467
PPK/INS LC	0.023	0.035	0.029	0.017	0.016	0.006	0.042	0.088	0.322
PPK/INS TC	0.022	0.035	0.028	0.017	0.017	0.007	0.046	0.082	0.333

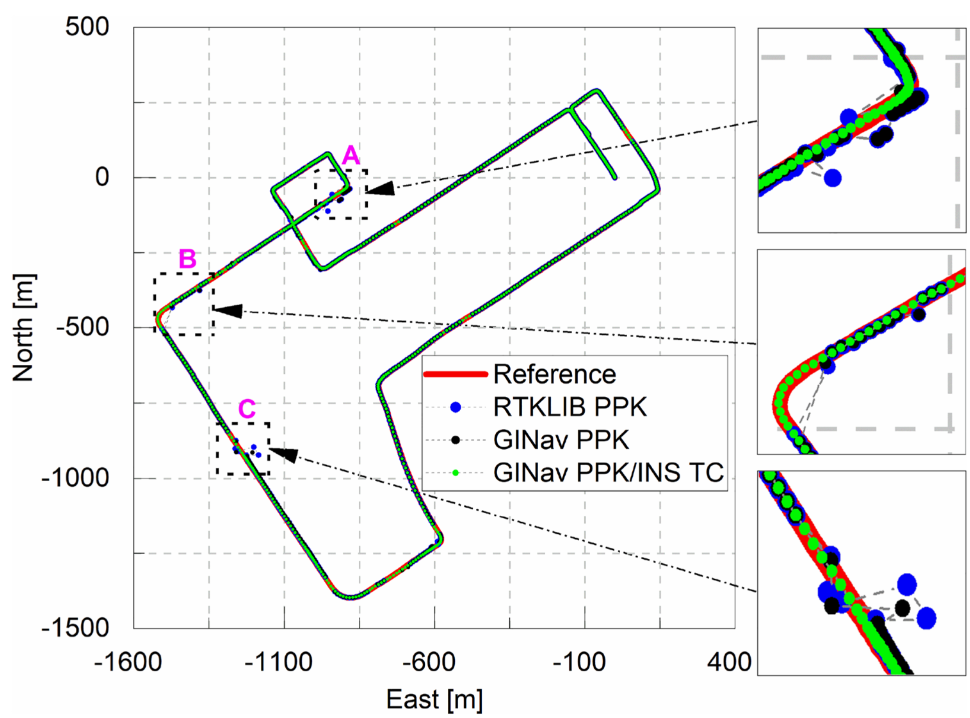

Fig. 6 2D trajectory determined by RTKLIB PPK (blue), GINav PPK (black) and GINav PPK/INS TC (green) schemes

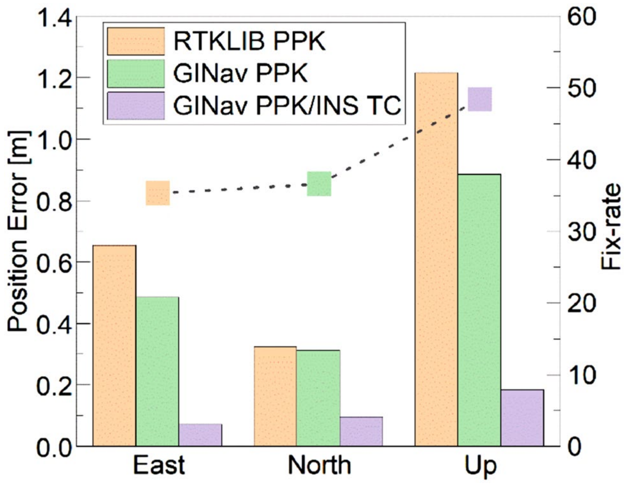

Fig. 7 Fixed position errors (histogram) and fix-rate (dotted line) derived from RTKLIB PPK, GINav PPK and GINav PPK/INS TC schemes

Table 2 Summary of results: east/north/up RMS errors of fixed positions and fix-rate

Scheme	Position Error (m)			Fix-rate
	East	North	Up	
RTKLIB PPK	0.656	0.324	1.216	35.3
GINav PPK	0.484	0.314	0.878	36.6
GINav PPK/INS TC	0.071	0.096	0.184	48.4

solutions in the A, B and C areas. However, the trajectory of the PPK mode (GNSS-only) provided by RTKLIB and GINav has many gaps and jumps. A comparison between the blue, black and green dashed lines in the figure indicates that the GNSS/INS integration mode is more practical and reliable than GNSS only mode in harsh environments. Figure 7 shows the comparison of fixed position errors and fix-rate for three schemes. It is obvious from the figure that the PPK/INS TC provided by GINav is superior to the GNSS-only PPK mode in terms of fixed solution accuracy and fix-rate. Moreover, the PPK mode of GINav is slightly superior to that of RTKLIB due to the stricter quality control of GINav. Table 2 summarizes the RMS errors of fixed position and fix-rate for three schemes. For PPK mode, the fix-rate is low, and the accuracy of fixed solutions can only reach the sub-meter level or even meter level. This poor accuracy might be due to wrong fixed integer ambiguities. In contrast, PPK/INS TC mode maintains a higher fix-rate and better accuracy, and it can achieve a centimeter-level in the east and north directions. Overall, the GINav software performs well for urban data processing, and the GNSS/INS integrated navigation system has significant advantages compared to GNSS-only in the harsh urban environment.

Summary and conclusions

GINav is a useful open-source software that focuses on the research and development of GNSS/INS integration algorithms and supports the usual GNSS positioning modes. It has a clear algorithm structure and a lot of comments and provides a user-friendly GUI and a plotting tool, which helps users quickly learn how to use it. Two experimental tests were conducted to validate and assess the performance of GINav. The results indicated that, in terms of GNSS/INS integration mode, GINav is able to provide navigation solutions comparable to general GNSS/INS integration standards, i.e., PPK/INS, PPP/INS, PPD/INS, and SPP/INS modes can achieve centimeter, small sub-meter, large sub-meter and meter level positioning accuracy, respectively. Furthermore, in a harsh urban environment, the GNSS/INS integration mode provided by GINav shows a significant improvement in positioning accuracy compared to the GNSS mode.

Currently, GINav is developed in the MATLAB environment. Considering navigation accuracy and data processing efficiency, we will further optimize the GNSS/INS integration algorithms and develop a C language-based GINav. The GINav software is available on The GPS Toolbox website at: https://geodesy.noaa.gov/gps-toolbox/. Some bugs may still exist in GINav. Comments and suggestions from users are welcome and can be sent 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 (UrbanNavDataset) or presented in the related paper (Chen et al. 2021).

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