2025;48(3):272-280

Earth sciences and subsoil use / ISSN 2686-9993 (print), 2686-7931 (online)
Науки о Земле и недропользование / ISSN 2686-9993 (print), 2686-7931 (online)

Original article
EDN: VIEUPY
DOI: 10.21285/2686-9993-2025-48-3-272-280

Comparative analysis of precise point positioning method performance integrating several global navigation satellite systems

Haofei Ban[a]✉, Vitaliy L. Ruposov[b], Vladimir M. Zhulikov[c]

[a]*Henan Polytechnic University, Jiaozuo, China*
[b,c]*Irkutsk National Research Technical University, Irkutsk, Russia*

Abstract. Precise Point Positioning technology is a high-accuracy positioning method of global navigation satellite systems that can achieve centimeter-level positioning accuracy using one receiver and precise orbit and time information. Unlike differential positioning methods, which rely on ground reference stations, Precise Point Positioning provides greater global coverage and significantly higher operational efficiency. The advancement of four global navigation satellite systems – GPS (Global Positioning System), GLONASS (Global Navigation Satellite System), GALILEO (global navigation satellite system), BDS (BeiDou navigation satellite system) – resulted in significant improvements in all signal transmission structures and satellite constellation positioning notifications that expanded the capabilities achieved by the modernization of these systems. The purpose of the study is to investigate the Precise Point Positioning technology performance performance for the four specified global navigation satellite systems by comparing the time they took to converge within a user-defined accuracy, analysis of positioning accuracy, and evaluation of the satellites used to derive the positioning solution. The results of the study will expand knowledge about multi-system applications of global navigation satellite systems and serve as a basis for innovative development of high-precision navigation and positioning technologies for global navigation satellite systems in the fields of surveying, mapping, and autonomous driving.

Keywords: global navigation satellite systems, BeiDou navigation satellite system, GLONASS (global navigation satellite system), precise point positioning, satellite navigation

For citation: Ban H., Ruposov V.L., Zhulikov V.M. Comparative analysis of precise point positioning method performance integrating several global navigation satellite systems. *Earth sciences and subsoil use.* 2025;48(3):272-280. https://doi.org/10.21285/2686-9993-2025-48-3-272-280. EDN: VIEUPY.

Научная статья
УДК 528.023

Сравнительный анализ эффективности метода точного позиционирования с использованием нескольких глобальных навигационных спутниковых систем

Х. Бань[a]✉, В.Л. Рупосов[b], В.М. Жуликов[c]

[a]*Хэнаньский политехнический университет, Цзяоцзо, Китай*
[b,c]*Иркутский национальный исследовательский технический университет, Иркутск, Россия*

Резюме. Технология точного точечного позиционирования (метод PPP, *от англ.:* Precise Point Positioning) представляет собой высокоточный метод позиционирования глобальных навигационных спутниковых систем, дает возможность определить местоположение сантиметровой точности с использованием только одного приемника и точной информации об орбите и времени. В отличие от методов дифференциального позиционирования метод PPP не зависит от наземных опорных станций, что обеспечивает большее глобальное покрытие и значительно повышает эксплуатационную эффективность. Благодаря усовершенствованию четырех глобальных навигационных спутниковых систем – GPS, ГЛОНАСС, GALILEO и BeiDou (BDS) – были значительно улучшены все структуры передачи сигналов, система оповещения о местоположении групп спутников и, следовательно, расширены возможности, достигнутые модернизацией этих систем. Целью проведенного исследования являлось изучение эффективности метода PPP для четырех указанных глобальных навигационных спутниковых систем на примере сравнения времени, необходимого для достижения заданной точности, оценки точности позиционирования и оценки спутников, используемых для получения решения о позиционировании. Результаты исследования расширят знания о мультисистемных приложениях глобальных навигационных спутниковых систем и послужат основой для инновационного развития технологий высокоточной навигации и позиционирования данных систем в таких областях, как геодезия, картография и автономное вождение.

Ключевые слова: глобальные навигационные спутниковые системы, навигационная спутниковая система BeiDou, ГЛОНАСС, точное позиционирование, спутниковая навигация

Для цитирования: Бань Х., Рупосов В.Л., Жуликов В.М. Сравнительный анализ эффективности метода точного позиционирования с использованием нескольких глобальных навигационных спутниковых систем // Науки о Земле и недропользование. 2025. Т. 48. № 3. С. 272–280. https://doi.org/10.21285/2686-9993-2025-48-3-272-280. EDN: VIEUPY.

Introduction

Precise Point Positioning (PPP), as a high-precision method of Global Navigation Satellite System (GNSS) positioning, can achieve centimeter-level accuracy using a single receiver with precise orbit and time products, essentially eliminating the reference station dependency required by standard differential methods [1–4]. Compared to Real-Time Kinematic and other relative positioning methods, PPP offers global availability without the need for a relatively high density ground infrastructure, which is advantageous for wide-area and remote applications.

PPP holds a number of advantages as it can provide global coverage with high operational efficiency and low requirements on the part of the user. For this reason, interest in using PPP approaches in both scientific and commercial applications is increasing.

As GNSS continue to develop and diversify, the landscape has evolved into four major global systems, including American Global Positioning System (GPS), Russian Global Navigation Satellite System (GLONASS), European Galileo Satellite Navigation System (GALILEO) and China's BeiDou Navigation Satellite System (BDS) [5–8]. Each of these systems continues to develop autonomously and is a part of a larger GNSS. In the early stages of 2023, GPS completed full deployment of its third generation of satellites, with the L5 band adding to signal quality, multipath mitigation, and capability in adverse environments. The GLONASS system was brought to full-constellation Code Division Multiple Access (CDMA) signal in 2022 to ameliorate the inter-frequency bias associated with its original Frequency Division Multiple Access (FDMA) system and for compatibility reasons. GALILEO is expected to achieve Full Operational Capability (FOC) in 2024, is providing multiple open and commercial services, with the most focus on the high-accuracy service on the E6 band and its potential to improve PPP. BDS-3 was the first GNSS to complete global networking in 2020 and, features an innovative geostationary orbit (GSO), also referred to as a geosynchronous equatorial orbit (GEO), inclined geostationary orbit (IGSO) and medium earth orbit (MEO) constellation, enabling improved regional service capabilities and ensuring time and frequency synchronization performance.

Currently, multi-system integrated positioning has become a mainstream trend in GNSS technology development [9–12]. Multi-GNSS constellation support improves satellite availability, enhances the geometry of the position solution, and increases the reliability of GNSS, especially in urban-canyon or other signal obstructed environments. However, major differences among systems in terms of constellation configuration, signal structure, and the spatio-temporal reference frameworks have created new technical issues related to inter-system compatibility and interoperability, error modeling and performance optimization. Multisystem PPP processing will require more sophisticated approaches for modeling inter-system biases, weighting signals, and using inconsistent observation models.

In this study, we systematically assess the PPP estimation performance of the four major GNSS, either separately or combined, under the same processing frameworks. This study aims to provide theoretical underpinnings and practical technical references for integrated multi-system applications, and ultimately contribute to promoting the innovative development of high accuracy navigation and positioning technologies in fields such as surveying and mapping, precision agriculture, remote sensing, and autonomous driving.

Materials and methods

The satellite constellation structures of Global Navigation Satellite Systems. GNSS employ carefully configured satellite constellations, characterized by distinct orbital altitudes, plane distributions, and inclination angles to optimize signal availability and system resilience. The following section elaborates on the key orbital parameters of these systems, including their constellation configurations, orbital planes, and backup strategies, highlighting the engineering considerations behind their design [13–15].

The GPS satellite navigation system of the American orbits at an altitude of about 20200 km. The whole system consists of 32 satellites distributed in six orbital planes. The inclination of the orbital plane of the satellite relative to the equatorial plane of the earth is 55 degrees, the right ascension of the ascending node of each orbital plane is 60 degrees, and the orbital period is 11 hours and 58 minutes (Fig. 1).

Russian GLONASS satellites orbit at an altitude of approximately 19100 km. The whole system consists of 26 satellites, which are distributed in three orbital planes. The orbital plane of the satellite has an orbital inclination of 64.8 degrees with respect to the equatorial plane of the Earth. The three orbital planes are 120 degrees apart, and the satellites in the same plane are 45 degrees apart, with an orbital period of 11 hours and 15 minutes (see Fig. 1).

The satellites of the European GALILEO satellite navigation system orbit at an altitude of 23616 km. The whole system consists of 32 satellites. The satellites are distributed in three orbital planes with an inclination of 56 degrees. The ascending nodes of the three orbits are 120 degrees apart on the equator, and the satellite has an operational period of 14 hours and 4 minutes. When a working satellite fails, the backup satellite will quickly enter the working position to replace its work, and the failed satellite will be transferred to an orbit 300 km higher than normal orbit (see Fig. 1).

China's BDS, which provides global services, adopts a mixed constellation composed of three kinds of orbit satellites. Compared with other satellite navigation systems, it has more high-orbit satellites and strong anti-occlusion capability, especially in low latitude areas. The whole system consists of 54 satellites, including 9 GEO satellites, 12 IGSO satellites and 33 MEO satellites. GEO satellites orbit at an altitude of 35786 km

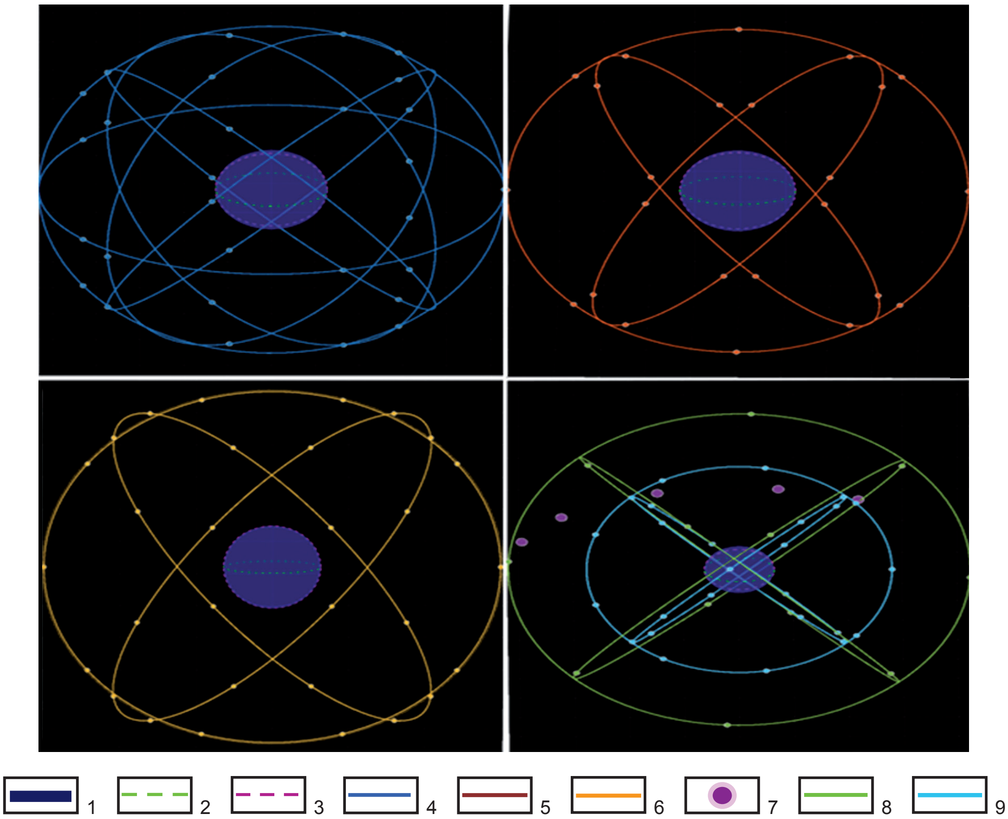

Fig. 1. Satellite constellation structures:
1 – Earth; 2 – equator; 3 – prime meridian; 4 – GPS satellite; 5 – GLONASS satellite;
6 – GALILEO satellite; 7 – BeiDou geostationary equatorial orbit;
8 – BeiDou inclined geostationary orbital plane; 9 – BeiDou medium Earth orbit

Рис. 1. Структуры групп спутников:
1 – Земля; 2 – экватор; 3 – нулевой меридиан; 4 – спутник GPS; 5 – спутник ГЛОНАСС;
6 – спутник ГАЛИЛЕО; 7 – геостационарная экваториальная орбита BeiDou;
8 – наклонная геостационарная орбитальная плоскость BeiDou; 9 – средняя околоземная орбита BeiDou

and are positioned at 58.75, 84, 110.5, 140 and 160 degrees East. The IGSO satellite has an orbital altitude of about 36000 km, three inclined synchronous orbital planes evenly distributed, an orbital inclination of 55 degrees, and three IGSO satellite sub-satellite point tracks coinciding with each other, with a crossing longitude of 118 degrees east longitude and a phase difference of 120 degrees. MEO satellites orbit at an altitude of 21500 km, with 27 satellites evenly distributed in three orbital planes with the inclination of 55 degrees (see Fig. 1).

Comparison of Signal Characteristics among Global Navigation Satellite Systems. Signal characteristics are important for assessing the performance and interoperability of a GNSS. Each major GNSS (GPS, GLONASS, Galileo, and BDS) has developed different frequency patterns and modulation schemes designed around their objective and application requirements [16–18].

The GPS is a typical example, transmitting signals from three single frequencies, L1 (1575.42 MHz), L2 (1227.60 MHz) and L5 (1176.45 MHz). Each frequency is the best representation of the system's capabilities. The L5 band has a relatively wide bandwidth of 24 MHz and uses Binary Phase Shift Keying (BPSK) [10] modulation to provide much improved code tracking accuracy and anti-interference capability. The L5 signal is approved for use within aeronautical radio navigation services Aeronautical Radio Navigation Services providing an assurance for any safety-critical applications such as aviation. The ability to add L2C and L1C signals also improved dual-frequency support and availability of signals.

In the same fashion, the BDS is also a tri-frequency system with B1I, B2a and B3I. Remember that B2a is aligned with GPS L5 and Galileo E5a to support seamless interoperability for multiple-system receivers. The BDS-3 system is also down to the modern B1C signal on 1575.42 MHz where it incorporates compatibility with GPS L1C and Galileo E1, which will allow for ease of combined tracking and signal resilience when operating under difficult conditions. Similar to the GNSS, there are also the BPSK and Binary Offset Carrier modulation types in BDS and which benefit multipath resilience and tracking accuracy.

The Galileo system offers four main signals: E1, E5a, E5b, and E6, but the guide is that the E5 signal utilizes Alternate Binary Offset Carrier modulation with an ultra-wide 51.15 MHz bandwidth, which will offer better code tracking performance and interference rejection. It also planned to have open access, civilian priority, and redundancy in signals; therefore, it is well placed to support high-accuracy or commercial services.

The GLONASS system used FDMA, for the original L1 and L2 signals, in which the satellites, even within the same family of GNSS, are transmitting at slightly different frequencies. This FDMA design minimizes intra-system interference, while concurrently creating inter-frequency biases that could create difficulties in integration with other systems, (for example CDMA systems). In addition, the GLONASS satellites have moved towards the deployment of some modern CDMA signals, such as L3OC and, therefore, provide an improvement to interoperability and signal performance.

The differences in the frequency design of GNSS signals (i. e., frequency separation), modulation bandwidths, and access techniques, and how they affect positioning accuracy, signal robustness, and system compatibility. In particular, systems with wideband signals (e. g., GPS L5, Galileo E5) or multiple carrier frequencies tend to transmit a more robust signals, that better resist interference of multipath, and allow for better mitigation of the effect of ionospheric delay. The global community adopts multi-GNSS positioning, and continuing the unification of signal designs, and overlaps in frequency and time between GPS, Galileo and BDS particularly, is crucial to support precise and reliable navigation services globally.

Precise Point Positioning Method. PPP is an advanced standalone GNSS positioning technique that provides users with centimeter-level positioning accuracy from a single receiver. The positioning accuracy is possible because PPP employs precise satellite orbit and clock products, which must be supplied publicly through international data centers. The PPP modeling relies on mission products that correct satellite trajectory and ancillary errors. Operationally, PPP improves positioning accuracy because it only partially relies on either single-frequency or dual-frequency GNSS receiver data, unlike traditional differential GNSS methods that rely on differential data from common-range reference station or base station networks to reduce shared error characteristics between the instruments. Deploying PPP is key in support of applications where deploying a reference station is difficult or unfeasible in remote applications or global applications. Many fields benefit from the consistent and reliable positioning performance over a large-scale that PPP represents because they have unlimited access to satellites and the expansive positioning performance of the GNSS. Fields that embrace a greater use of this technology include geodesy; surveying; precision agriculture; and autonomous vehicles. The advancements in precise satellite data and real time corrections mean there is an increasing interest in a strong alternative for positioning that PPP represents in the worldwide position community.

The pseudo-range and carrier phase observation equations for dual-frequency GNSS signals are formulated as:

$$P_r^s(f) = \rho_r^s + c(\delta t_r - \delta t^s) + T_r^s + I_r^s(f) + \\ + d_r^P(f) - d_s^P(f) - \varepsilon_p,$$

$$\Phi_r^s(f) = \rho_r^s + c(\delta t_r - \delta t^s) + T_r^s - I_r^s(f) + \\ + \lambda_f N_r^s + d_r^\Phi(f) - d_s^\Phi(f) - \varepsilon_\Phi,$$

where f is frequency; P_r^s is geometric range; δt_r and δt^s are receiver and satellite clock errors; T_r^s is tropospheric delay; I_r^s is ionospheric delay; N_r^s is carrier phase ambiguity ambiguity; d_r^P and d_s^P are pseudo-range hardware biases of receiver and satellite; d_r^Φ and d_s^Φ are phase hardware biases of receiver and satellite; ε_p and ε_Φ are measurement noise and multipath error.

During PPP processing, satellite positions and clock corrections are substituted with precise products provided by entities such as International GNSS Service (IGS). This improves positioning accuracy [19–20]. Ionospheric delays are reduced using dual-frequency ionosphere free linear combinations or externally corrected using ionospheric models. Tropospheric delays are often treated as zenith wet delay parameters and projected using correct mapping functions. The estimated state vector will typically contain the receiver's three-dimensional coordinates, receiver clock bias, tropospheric delay parameters and carrier phase ambiguities. When using multi-frequency observations, the estimated state vector could also include parameters remediate inter-frequency biases.

Results and discussion

The research systematically assesses PPP performance of the four main systems (GPS, GLONASS, GALILEO, and BDS) based on raw GNSS data collected by the UM982 chip produced by Unicore.

There are roughly 43 satellites in the multi-system solution. For the individual systems approximately 9 satellites are used for the GPS solution, 7 for GLONASS, 10 for GALILEO and 16 for BDS. This shows how many more satellites are available using a multi-system solution instead of any one individual system (Fig. 2).

Multi-system integration shows distinct advantages in positioning accuracy (Fig. 3). It can achieve decimeter-level accuracy in east (E), north (N) and up (U) directions in 3 minutes, centimeter accurate is achieved in 20 minutes. By contrast, GPS only takes 6 and 23 minutes, respectively for decimeter and centimeter-level

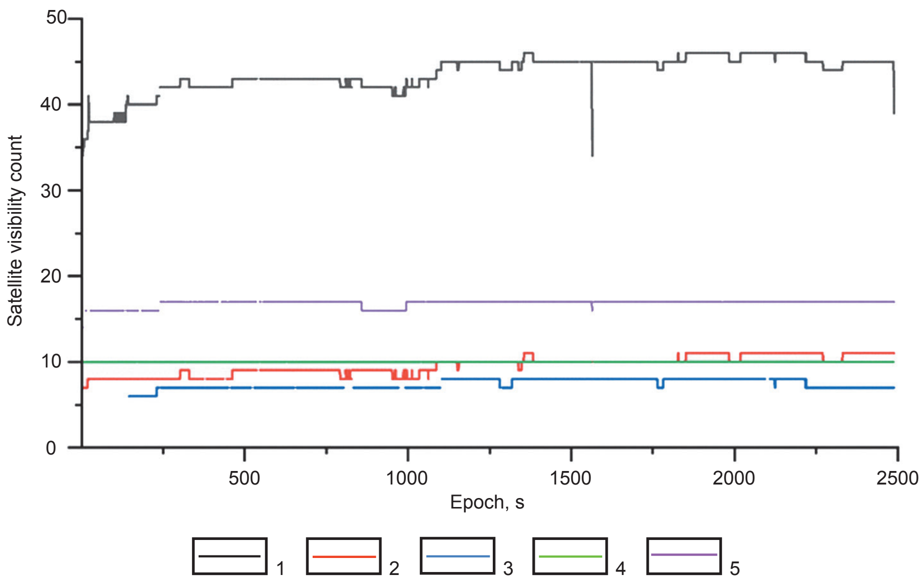

Fig. 2. Number of satellites observed:
1 – general; 2 – GPS; 3 – GLONASS; 4 – GALILEO; 5 – BeiDou
Рис. 2. Количество наблюдаемых спутников:
1 – общее; 2 – GPS; 3 – ГЛОНАСС; 4 – ГАЛИЛЕО; 5 – BeiDou

accuracy; GLONASS, which takes 11 minutes each for decimeter and centimeter accuracies; GALILEO, which takes 11 minutes for decimeter and 30 minutes for centimeter, and BDS with decimeter and centimeter accuracies in 10 and 28 minutes, respectively. Both GPS and BDS had the best local conditions for a rapid acquisition and high accuracy. GPS has the advantage of a mature constellation structure and high quality signals, which allows rapid convergence and high accuracy. BDS, because it is GEO+IGSO+MEO hybrid provides the best visibility of satellites worldwide. GLONASS requires a hybrid FDMA and CDMA access scheme, therefore, at a given time, fewer satellites can be accounted in your PPP solution, because of a sparse constellation, which requires a longer convergence time with slight differences in accuracy in comparison with GPS and BDS. GALILEO is currently limited in satellites, however the complex signal structure and wide-band Alternate Binary Offset Carrier modulation allows enhanced multipath suppression and anti-interference performance.

Therefore, the experiments performed suggest multi-system integration does not only increase the number of available satellites but also increases PPP convergence speed and final position accuracy.

Conclusion

This research systematically compares and analyzes the PPP positioning performance of the four major GNSS: GPS, GLONASS, GALILEO, and BDS. The experiments show that the integrated PPP (multi system PPP combination) approach can greatly increase the number of available satellites, reduce the time to reach a given positioning accuracy and lead to better positioning performance.

Both GPS and BDS show the best PPP positioning performance, achieving decimeter (or sub-decimeter, even centimeter) levels positioning at speeds of less than a minute and in an applicable quantity of areas. Due to the constellation layout and legal limitations on the use of GLONASS signals (i. e. result in less satellites being used),

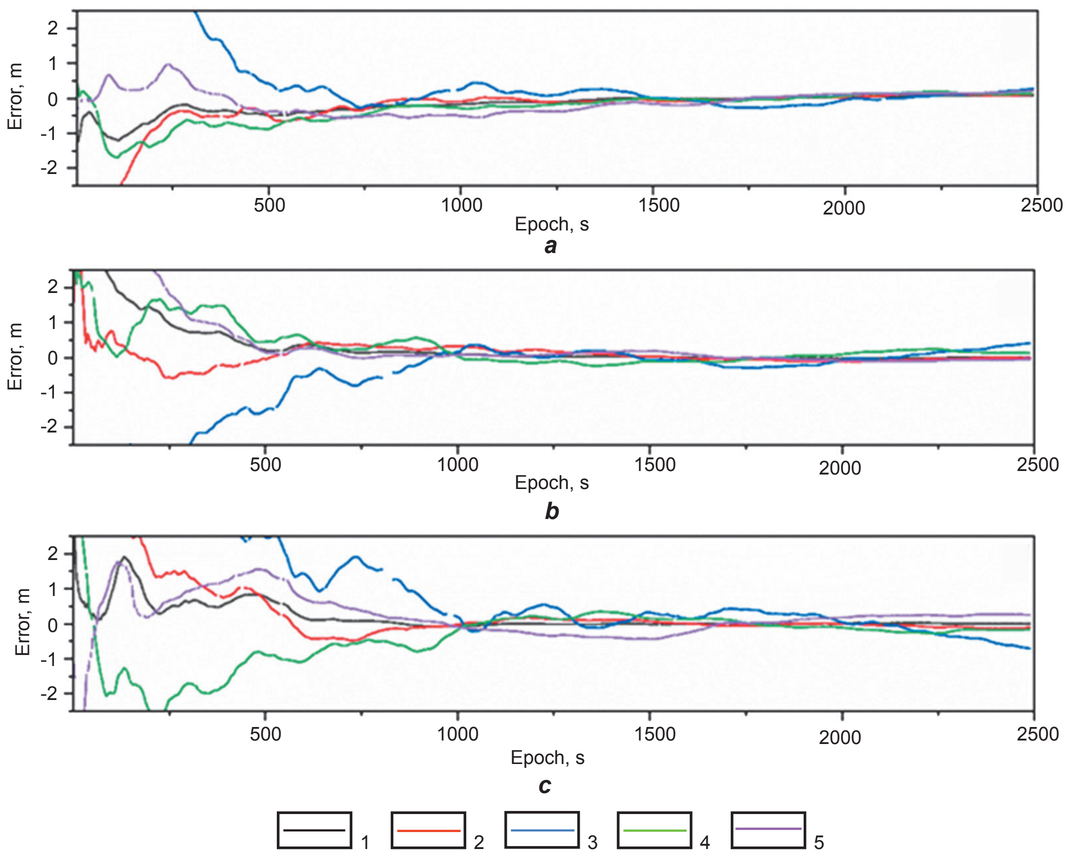

Fig. 3. Positioning error:
a – east; b – north; c – up
1 – general; 2 – GPS; 3 – GLONASS; 4 – GALILEO; 5 – BeiDou
Рис. 3. Ошибка позиционирования:
a – восток; b – север; c – вверх
1 – общая; 2 – GPS; 3 – ГЛОНАСС; 4 – ГАЛИЛЕО; 5 – BeiDou

GLONASS had a slightly slower convergence time and lower precision. GALILEO at the time of these experiments had a limited number of satellites but also had powerful anti-interference and multipath performance due to the advanced signal structure and wideband modulation.

Through the use of multi-system integrated PPP, an improvement in reliability, and an improvement of accuracy was versus a (not multi-system system PPP only) system underway, and also an improvement in robustness in complex and changing environment. After the constellation, the signal, and the unit references of each system are optimized, we can notice that multi-system integrated PPP technology is increasingly enhancing navigation and positioning in all high-precision fields including surveying, autonomous driving, and intelligent transportation.

References

1. Choi B.-K., Cho C.-H., Lee S.J. Multi-GNSS kinematic precise point positioning: some results in South Korea. *Journal of Positioning, Navigation, and Timing*. 2017;6(1):35-41. https://doi.org/10.11003/JPNT.2017.6.1.35.

2. Fan C., Yao Z., Wang S., Xing J. Pseudolite system-augmented GNSS real-time kinematic PPP. *Journal of Geodesy*. 2022;96:77. https://doi.org/10.1007/s00190-022-01663-4.

3. Gao Z., Zhang H., Ge M., Niu X., Shen W., Wickert J., et al. Tightly coupled integration of multi-GNSS PPP and MEMS inertial measurement unit data. *GPS Solutions*. 2017;21(2):377-391. https://doi.org/10.1007/s10291-016-0527-z.

4. Li Y., Cai C. A mixed single- and dual-frequency quad-constellation GNSS precise point positioning approach on Xiaomi Mi8 smartphones. *The Journal of Navigation*. 2022;75(4):849-863. https://doi.org/10.1017/S0373463322000145.

5. Hamza V., Stopar B., Sterle O., Pavlovčič-Prešeren P. Recent advances and applications of low-cost GNSS receivers: a review. *GPS Solutions.* 2025;29:56. https://doi.org/10.1007/s10291-025-01815-x.

6. Jin S., Meng X., Dardanelli G., Zhu Y. Multi-Global Navigation Satellite System for Earth observation: recent developments and new progress. *Remote Sensing.* 2024;16(24):4800. https://doi.org/10.3390/rs16244800.

7. Jin S., Wang Q., Dardanelli G. A review on Multi-GNSS for Earth observation and emerging applications. *Remote Sensing.* 2022;14(16):3930. https://doi.org/10.3390/rs14163930.

8. Hamza V., Stopar B., Sterle O., Pavlovčič-Prešeren P. Observations and positioning quality of low-cost GNSS receivers: a review. *GPS Solutions.* 2024;28:149. https://doi.org/10.1007/s10291-024-01686-8.

9. An X., Meng X., Jiang W. Multi-constellation GNSS precise point positioning with multi-frequency raw observations and dual-frequency observations of ionospheric-free linear combination. *Satellite Navigation*. 2020;1:7. https://doi.org/10.1186/s43020-020-0009-x.

10. Liang K., Hao S., Yang Z., Wang J. A Multi-Global Navigation Satellite System (GNSS) time transfer method with Federated Kalman Filter (FKF). *Sensors*. 2023;23(11):5328. https://doi.org/10.3390/s23115328.

11. Ren X., Zhang X., Xie W, Zhang K., Yuan Y., Li X. Global ionospheric modelling using Multi-GNSS: BeiDou, Galileo, GLONASS and GPS. *Scientific Reports*. 2016;6:33499. https://doi.org/10.1038/srep33499.

12. Yoo W.J., Kim L., Lee Y.D., Lee T.G., Lee H.K. Design and implementation of SDR-based multi-constellation multi-frequency real-time A-GNSS receiver utilizing GPGPU. *Journal of Positioning, Navigation, and Timing.* 2021;10(4):315-333. https://doi.org/10.11003/JPNT.2021.10.4.315.

13. Chen J., Wang J., Zhang Y., Yang S., Chen Q., Gong X. Modeling and assessment of GPS/BDS combined precise point positioning. *Sensors*. 2016;16(7):1151. https://doi.org/10.3390/s16071151.

14. Gao M., Cao Z., Meng Z., Tan C., Zhu H., Huang L. Algorithms research and precision comparison of different frequency combinations of BDS-3/GPS/Galileo for precise point positioning in Asia-Pacific region. *Sensors*. 2023:23(13):5935. https://doi.org/10.3390/s23135935.

15. Hou Z., Zhou F. Assessing the performance of precise point positioning (PPP) with the fully serviceable multi-GNSS constellations: GPS, BDS-3, and Galileo. *Remote Sensing*. 2023;15(3):807. https://doi.org/10.3390/rs15030807.

16. Liu W., Liu J., Xie J., Jiao B. Signal-in-space range error of the global BeiDou Navigation Satellite System and comparison with GPS, GLONASS, Galileo, and QZSS. *Journal of Surveying Engineering.* 2023;149(1). https://doi.org/10.1061/(ASCE)SU.1943-5428.0000413.

17. Zhang Z., Pan L. Current performance of open position service with almost fully deployed multi-GNSS constellations: GPS, GLONASS, Galileo, BDS-2, and BDS-3. *Advances in Space Research*. 2022;69(5):1994-2019. https://doi.org/10.1016/j.asr.2021.12.002.

18. Zheng Y., Zheng F., Yang C., Nie G., Li S. Analyses of GLONASS and GPS plus GLONASS precise positioning performance in different latitude regions. *Remote Sensing*. 2022;14(18):4640. https://doi.org/10.3390/rs14184640.

19. Hou P., Zha J., Liu T., Zhang B. Recent advances and perspectives in GNSS PPP-RTK. *Measurement Science and Technology*. 2023;34(5):051002. https://doi.org/10.1088/1361-6501/acb78c.

20. Zhao Q., Guo J., Zuo H., Gong X., Guo W., Gu S. Comparison of time transfer of IF-PPP, GIM-PPP, and RIM-PPP. *GPS Solutions*. 2023;27:99. https://doi.org/10.1007/s10291-023-01424-6.

Список источников

1. Choi B.-K., Cho C.-H., Lee S.J. Multi-GNSS kinematic precise point positioning: some results in South Korea // Journal of Positioning, Navigation, and Timing. 2017. Vol. 6. Iss. 1. P. 35–41. https://doi.org/10.11003/JPNT.2017.6.1.35.

2. Fan C., Yao Z., Wang S., Xing J. Pseudolite system-augmented GNSS real-time kinematic PPP // Journal of Geodesy. 2022. Vol. 96. P. 77. https://doi.org/10.1007/s00190-022-01663-4.

3. Gao Z., Zhang H., Ge M., Niu X., Shen W., Wickert J., et al. Tightly coupled integration of multi-GNSS PPP and MEMS inertial measurement unit data // GPS Solutions. 2017. Vol. 21. Iss. 2. P. 377–391. https://doi.org/10.1007/s10291-016-0527-z.

4. Li Y., Cai C. A mixed single- and dual-frequency quad-constellation GNSS precise point positioning approach on Xiaomi Mi8 smartphones // The Journal of Navigation. 2022. Vol. 75. Iss. 4. P. 849–863. https://doi.org/10.1017/S0373463322000145.

5. Hamza V., Stopar B., Sterle O., Pavlovčič-Prešeren P. Recent advances and applications of low-cost GNSS receivers: a review // GPS Solutions. 2025. Vol. 29. P. 56. https://doi.org/10.1007/s10291-025-01815-x.

6. Jin S., Meng X., Dardanelli G., Zhu Y. Multi-Global Navigation Satellite System for Earth observation: recent developments and new progress // Remote Sensing. 2024. Vol. 16. Iss. 24. P. 4800. https://doi.org/10.3390/rs16244800.

7. Jin S., Wang Q., Dardanelli G. A review on Multi-GNSS for Earth observation and emerging applications // Remote Sensing. 2022. Vol. 14. Iss. 16. P. 3930. https://doi.org/10.3390/rs14163930.

8. Hamza V., Stopar B., Sterle O., Pavlovcic-Preseren P. Observations and positioning quality of low-cost GNSS receivers: a review // GPS Solutions. 2024. Vol. 28. P. 149. https://doi.org/10.1007/s10291-024-01686-8.

9. An X., Meng X., Jiang W. Multi-constellation GNSS precise point positioning with multi-frequency raw observations and dual-frequency observations of ionospheric-free linear combination // Satellite Navigation. 2020. Vol. 1. P. 7. https://doi.org/10.1186/s43020-020-0009-x.

10. Liang K., Hao S., Yang Z., Wang J. A Multi-Global Navigation Satellite System (GNSS) time transfer method with Federated Kalman Filter (FKF) // Sensors. 2023. Vol. 23. Iss. 11. P. 5328. https://doi.org/10.3390/s23115328.

11. Ren X., Zhang X., Xie W, Zhang K., Yuan Y., Li X. Global ionospheric modelling using Multi-GNSS: BeiDou, Galileo, GLONASS and GPS // Scientific Reports. 2016. Vol. 6. P. 33499. https://doi.org/10.1038/srep33499.

12. Yoo W.J., Kim L., Lee Y.D., Lee T.G., Lee H.K. Design and implementation of SDR-based multi-constellation multi-frequency real-time A-GNSS receiver utilizing GPGPU // Journal of Positioning, Navigation, and Timing. 2021. Vol. 10. Iss. 4. P. 315–333. https://doi.org/10.11003/JPNT.2021.10.4.315.

13. Chen J., Wang J., Zhang Y., Yang S., Chen Q., Gong X. Modeling and assessment of GPS/BDS combined precise point positioning // Sensors. 2016. Vol. 16. Iss. 7. P. 1151. https://doi.org/10.3390/s16071151.

14. Gao M., Cao Z., Meng Z., Tan C., Zhu H., Huang L. Algorithms research and precision comparison of different frequency combinations of BDS-3/GPS/Galileo for precise point positioning in Asia-Pacific region // Sensors. 2023. Vol. 23. Iss. 13. P. 5935. https://doi.org/10.3390/s23135935.

15. Hou Z., Zhou F. Assessing the performance of precise point positioning (PPP) with the fully serviceable multi-GNSS constellations: GPS, BDS-3, and Galileo // Remote Sensing. 2023. Vol. 15. Iss. 3. P. 807. https://doi.org/10.3390/rs15030807.

16. Liu W., Liu J., Xie J., Jiao B. Signal-in-space range error of the global BeiDou Navigation Satellite System and comparison with GPS, GLONASS, Galileo, and QZSS // Journal of Surveying Engineering. 2023. Vol. 149. Iss. 1. https://doi.org/10.1061/(ASCE)SU.1943-5428.0000413.

17. Zhang Z., Pan L. Current performance of open position service with almost fully deployed multi-GNSS constellations: GPS, GLONASS, Galileo, BDS-2, and BDS-3 // Advances in Space Research. 2022. Vol. 69, Iss. 5. P. 1994–2019. https://doi.org/10.1016/j.asr.2021.12.002.

18. Zheng Y., Zheng F., Yang C., Nie G., Li S. Analyses of GLONASS and GPS plus GLONASS precise positioning performance in different latitude regions // Remote Sensing. 2022. Vol. 14. Iss. 18. P. 4640. https://doi.org/10.3390/rs14184640.

19. Hou P., Zha J., Liu T., Zhang B. Recent advances and perspectives in GNSS PPP-RTK // Measurement Science and Technology. 2023. Vol. 34. Iss. 5. P. 051002. https://doi.org/10.1088/1361-6501/acb78c.

20. Zhao Q., Guo J., Zuo H., Gong X., Guo W., Gu S. Comparison of time transfer of IF-PPP, GIM-PPP, and RIM-PPP // GPS Solutions. 2023. Vol. 27. P. 99. https://doi.org/10.1007/s10291-023-01424-6.

Information about the authors / Информация об авторах

Haofei Ban,
Ph.D. (Surveying & Geoinformation),
School of Surveying and Geoinformation Engineering,
Henan Polytechnic University,
Jiaozuo, China,
✉ bhf@home.hpu.edu.cn
https://orcid.org/0000-0002-9631-2716
Бань Хаофэй,
кандидат наук в области геодезии и картографии,
Школа геодезии и геоинформационной инженерии,
Хэнаньский политехнический университет,
г. Цзяоцзо, Китай,
✉ bhf@home.hpu.edu.cn
https://orcid.org/0000-0002-9631-2716

Vitaliy L. Ruposov,
Cand. Sci. (Geol. & Mineral.), Associate Professor,
Associate Professor of the Department of Mine Surveying and Geodesy,
Institute of Subsoil Use,
Irkutsk National Research Technical University,
Irkutsk, Russia,
ruposov@istu.edu
https://orcid.org/0000-0003-2202-9034
Рупосов Виталий Леонидович,
кандидат геолого-минералогических наук, доцент,
доцент кафедры маркшейдерского дела и геодезии,
Институт недропользования,
Иркутский национальный исследовательский технический университет,
г. Иркутск, Россия,
ruposov@istu.edu
https://orcid.org/0000-0003-2202-9034

Vladimir M. Zhulikov,
Student,
Baikal School of BRICS,
Irkutsk National Research Technical University,
Irkutsk, Russia,
vladmir.zhulikov@bk.ru
https://orcid.org/0009-0000-3637-9567
Жуликов Владимир Михайлович,
студент,
Байкальский институт БРИКС,
Иркутский национальный исследовательский технический университет,
г. Иркутск, Россия,
vladmir.zhulikov@bk.ru
https://orcid.org/0009-0000-3637-9567

Contribution of the authors / Вклад авторов

Haofei Ban – investigation, methodology, formal analysis, validation, visualization, writing – original draft.
Vitaliy L. Ruposov – conceptualization, project administration, resources.
Vladimir M. Zhulikov – data curation, writing – editing.
Х. Бань – проведение исследования, разработка методологии, формальный анализ, валидация результатов, визуализация, написание черновика рукописи.
В.Л. Рупосов – разработка концепции, административное руководство исследовательским проектом, предоставление ресурсов.
В.М. Жуликов – курирование данных, редактирование рукописи.

Conflict of interests / Конфликт интересов

The authors declare no conflicts of interests.
Авторы заявляют об отсутствии конфликта интересов.

The final manuscript has been read and approved by all the co-authors.
Все авторы прочитали и одобрили окончательный вариант рукописи.

Information about the article / Информация о статье

The article was submitted 30.04.2025; approved after reviewing 30.05.2025; accepted for publication 19.06.2025.
Статья поступила в редакцию 30.04.2025; одобрена после рецензирования 30.05.2025; принята к публикации 19.06.2025.