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GNSS - TECHNOLOGIES AND SATELLITE GEODESY OF THE NEW GENERATION

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Annotation. *This paper presents a narrative review of modern approaches to the application of Global Navigation Satellite Systems (GNSS) in geodesy and geospatial support. The aim of the study is to summarize current high-precision satellite positioning technologies and to identify the prospects for their application in the context of the digital transformation of the geodetic sector. The review is based on an analysis of scientific publications and official documents devoted to Real-Time Kinematic (RTK), Network RTK (NRTK), Precise Point Positioning (PPP), PPP-RTK, State Space Representation (SSR), the Galileo High Accuracy Service (HAS), as well as the integration of GNSS with unmanned aerial vehicles and geographic information systems. The analysis covers current approaches to high-precision positioning, the use of multi-constellation and multi-frequency GNSS observations, issues of navigation signal integrity and authentication, and the prospects for the development of high-accuracy satellite positioning services.*

The analysis systematized the main characteristics of RTK, NRTK, PPP, and PPP-RTK technologies according to positioning accuracy, convergence time, dependence on ground-based reference infrastructure, spatial coverage, and suitability for operation under different observation conditions. RTK and NRTK provide rapid high-precision positioning when access to reference infrastructure is available, whereas PPP offers greater independence from local reference stations but requires a longer convergence period. PPP-RTK combines the advantages of global PPP coverage with faster convergence through the use of additional correction information. The study also demonstrates that achieving centimeter- or millimeter-level positioning accuracy depends on receiver characteristics, observation duration, satellite geometry and availability, correction quality, and data processing methodology.

The study identifies the use of the Galileo High Accuracy Service (HAS), State Space Representation (SSR) corrections, the integration of GNSS with unmanned aerial vehicles, geographic information systems, and other sensor technologies, as well as the application of machine learning methods to improve positioning reliability, as promising directions for the development of GNSS technologies. The obtained results may be used to select the most appropriate high-precision GNSS positioning technology depending on accuracy requirements, observation conditions, and the availability of reference infrastructure.

Key words: *GNSS technologies, satellite geodesy, GPS, Galileo, GLONASS, BeiDou, RTK, Network RTK, PPP, PPP-RTK, SSR corrections, Galileo HAS, high-precision positioning, geospatial data.*

Relevance. The modern development of geodesy is inextricably linked with the wide use of global navigation satellite systems (GNSS), which are the basis of high-precision coordinate support in geodesy, cartography, cadastre, construction, monitoring of engineering structures and other areas. The increase in requirements for the accuracy, efficiency and reliability of coordinate determinations necessitates

the improvement of high-precision satellite positioning technologies and the substantiation of the conditions for their effective application.

Despite a significant number of studies devoted to individual GNSS positioning technologies, the results of their comparative assessment are not sufficiently summarized in the scientific literature. In particular, modern approaches to the application of RTK, Network RTK, Precise Point Positioning (PPP) and PPP-RTK, as well as the analysis of the latest directions of development related to the use of State Space Representation (SSR) corrections, the Galileo High Accuracy Service (HAS), multi-system and multi-frequency observations. The issues of choosing the optimal technology depending on the requirements for accuracy, observation conditions and availability of reference infrastructure remain insufficiently researched [1].

The purpose of the work is to conduct a structured narrative analysis of modern scientific publications on the development of high-precision GNSS positioning, comparison of RTK, Network RTK, PPP and PPP-RTK technologies, as well as generalization of modern trends in the development of satellite geodesy and prospects for using the latest high-precision positioning services.

Analysis of recent research and publications. The analysis of modern scientific publications shows that the main directions of development of global navigation satellite systems (GNSS) are the improvement of Precise Point Positioning (PPP), Real-Time Kinematic (RTK), Network RTK (NRTK) and PPP-RTK technologies. Research demonstrates a shift from the use of separate positioning methods to multi-system and multi-frequency solutions, in which accuracy, time to obtain a coordinate solution, availability of corrections and resistance to external influences are simultaneously taken into account [2].

In most publications, PPP-RTK is seen as a promising direction for the development of high-precision positioning, as this technology combines the advantages of PPP and RTK and provides a reduction in convergence time through the use of accurate orbital, temporal and atmospheric corrections. At the same time, the authors note that the effectiveness of PPP-RTK depends on the way corrections

are formed, the characteristics of the satellite constellation and the availability of the relevant services [3].

Analysis of sources shows that Network RTK ensures the expansion of the high-precision positioning zone thanks to the use of networks of permanently operating reference stations. At the same time, the main factors of NRTK efficiency are the density of the reference network, the reliability of the telecommunications infrastructure and the continuity of correction transmission [4].

A separate block of research is devoted to multi-system and multi-frequency GNSS observations. The authors note that the simultaneous use of GPS, Galileo, BeiDou and GLONASS increases the availability of satellite observations and improves the geometry of the satellite constellation, while multi-frequency measurements contribute to more efficient elimination of ionospheric errors. However, it is emphasized that the accuracy of coordinate determinations depends not only on the number of satellites, but also on the conditions of signal reception, their geometry and multipath [5].

In modern literature, considerable attention is paid to ensuring the reliability of GNSS positioning in conditions of a complex environment. Research focuses on the integration of GNSS with inertial navigation systems (INS), LiDAR and other sensors, as well as the development of methods to detect anomalous observations and control the integrity of the navigation solution.

A separate area of research is related to the use of machine learning methods for processing GNSS data. Scientific works demonstrate the possibility of using artificial intelligence algorithms to detect anomalies, classify signal propagation conditions and model multipath errors, although their effectiveness depends significantly on the characteristics of training samples and operating conditions [6].

Also, a significant number of publications are devoted to the use of GNSS for monitoring deformations of the earth's surface and engineering structures. The authors note the effectiveness of RTK for operational measurements and PPP for long-term observations, emphasizing that the validity of results is determined by the stability of time series and the quality of mathematical data processing [7].

At the same time, the literature analysis showed an insufficient number of generalizing studies devoted to a comprehensive assessment of the reliability of GNSS infrastructure, a comparative analysis of modern high-precision positioning technologies and the use of the latest services, in particular SSR corrections and Galileo High Accuracy Service (HAS), in conditions of limited reference infrastructure and increased security risks [8].

The purpose of this study there is a narrative review of the current state and prospects for the development of global navigation satellite systems (GNSS) technologies in satellite geodesy, as well as a comprehensive comparative analysis of the main methods of high-precision positioning – Real-Time Kinematic (RTK), Network RTK, Precise Point Positioning (PPP) and PPP-RTK. Special attention is paid to the evaluation of the specified methods according to the criteria of accuracy, convergence time of the coordinate solution, the need for reference infrastructure, coverage area, availability and delay of corrections, the possibility of working in real time and resistance to difficult observation conditions.

A separate task of the study is to generalize modern approaches to the use of multi-system and multi-frequency GNSS observations, State Space Representation (SSR), Galileo High Accuracy Service (HAS), as well as to analyze the role of technologies for ensuring the integrity and authentication of navigation signals in increasing the reliability of coordinate solutions. The study is also aimed at determining the impact of atmospheric errors, multipath propagation of signals, urban development, radio interference and other factors on the quality of GNSS positioning.

Research materials and methods. The research was carried out in the format of a structured narrative review aimed at summarizing the current state and prospects for the development of global navigation satellite systems (GNSS) in satellite geodesy, as well as at a comparative assessment of the main technologies of high-precision positioning. The structured narrative review is chosen in view of the comprehensive nature of the study, which covers Real-Time Kinematic (RTK), Network RTK (NRTK), Precise Point Positioning (PPP), PPP-RTK, multi-system and multi-frequency GNSS surveillance, State Space Representation (SSR), Galileo

High Accuracy Service (HAS), issues of integrity and authentication of navigation signals, the and GNSS integration with inertial navigation systems (INS), unmanned aerial vehicles, LiDAR, geographic information systems and machine learning techniques [9].

The research materials were peer-reviewed scientific publications of domestic and foreign authors, review and experimental studies, official technical documentation of international GNSS services, regulatory and technical materials and open scientific and information resources. The search for scientific sources was carried out in the Scopus and Web of Science Core Collection databases, as well as in Google Scholar. To clarify the technical characteristics of satellite systems and high-precision positioning services, official materials of the European Space Agency (ESA), the European Space Program Agency (EUSPA) and official Galileo information resources were additionally processed.

The search for sources was carried out using combinations of keywords: «GNSS», «Global Navigation Satellite Systems», «RTK», «Real-Time Kinematic», «Network RTK», «NRTK», «Precise Point Positioning», «PPP», «PPP-RTK», «State Space Representation», «SSR corrections», «Galileo High Accuracy Service», «Galileo HAS», «GNSS integrity», «GNSS authentication», «GNSS jamming», «GNSS spoofing», «GNSS multipath», «NLOS GNSS», «GNSS/INS integration», «GNSS machine learning», and «high-precision GNSS positioning». In the search strategies, logical operators AND and OR were used, which made it possible to combine general and specialized terms according to the subject of the study.

The main search time interval covered scientific publications and technical materials published between 2015 and 2026. The choice of this period is due to the need to cover the modern stage of development of multi-system and multi-frequency GNSS technologies, PPP-RTK, SSR corrections, high-precision positioning services and intelligent methods of processing satellite observations. At the same time, individual fundamental works published before 2015 were included in the analysis in cases where they were of fundamental importance for understanding the theoretical and methodological foundations of RTK, NRTK, PPP or PPP-RTK.

The source selection procedure consisted of four consecutive stages. At the first stage, publications were identified by keywords and search queries. In the second stage, the removal of duplicate records and preliminary analysis of names and annotations were carried out. In the third stage, the evaluation of the full texts of the publications was performed for compliance with the defined inclusion and exclusion criteria. At the fourth stage, the selected sources were grouped by thematic areas and used for comparative and narrative analysis [10].

The analysis included sources that met at least one of the following criteria: considered RTK, NRTK, PPP or PPP-RTK technologies; analyzed multi-system or multi-frequency GNSS observations; investigated SSR corrections or Galileo HAS; contained assessments of accuracy, convergence time, availability or reliability of coordinate solutions; analyzed the influence of ionospheric and tropospheric delays, multipath propagation of signals, NLOS signals and other sources of errors; considered the issues of integrity and authentication of GNSS signals effects of jamming and spoofing; or were devoted to the integration of GNSS with INS, LiDAR, UAVs, GIS and machine learning techniques.

Exclusion criteria were: duplicated publications; sources that did not correspond to the topic of high-precision GNSS positioning; materials without a sufficient description of the methodology or research results; publications in which GNSS was used only as an auxiliary tool without evaluating positioning characteristics; as well as unverified information resources without established authorship or official status. Official documents of relevant operators and organizations were used to determine the technical characteristics of GNSS services, and peer-reviewed international scientific publications were preferred to evaluate the actual accuracy and practical effectiveness of technologies.

A total of 186 information records were identified in the search process. After removing 34 duplicate records and conducting an initial analysis of names and annotations, 152 sources were selected for full-text processing. According to the results of the evaluation of the full texts, 86 sources that were included in the final narrative analysis met the research criteria. Among them, 68 were peer-reviewed

scientific publications, 10 – review scientific works, and 8 – were official technical and informational materials of international GNSS services. Selected sources were distributed according to thematic areas: RTK and NRTK methods; PPP and PPP-RTK; multi-system and multi-frequency technologies; SSR corrections and Galileo HAS; accuracy and convergence time; GNSS in difficult conditions; integrity and authentication of signals; jamming and spoofing; integration of GNSS with INS and other sensor systems; application of machine learning for processing GNSS data.

For each selected source, the year of publication, type of source, GNSS technology studied, satellite systems and frequency ranges, positioning method, observation conditions, type of corrections used, accuracy of coordinate determinations, convergence time, duration of observations, type of reference infrastructure, availability of correction transmission channels and main limitations of the technology were analyzed. This approach provided an opportunity to compare research results obtained in different experimental and practical conditions.

The comparative analysis of RTK, NRTK, PPP and PPP-RTK was carried out according to a single analytical matrix, which included the following criteria: positioning accuracy; convergence time; the possibility of working in real time; the need for local or network reference infrastructure; spatial coverage area; type and method of transmission of corrections; delay of corrections; dependence on telecommunication infrastructure; resistance to communication loss; requirements for user equipment; resistance to multipath of signals and urban environment; the possibility of application for high-precision monitoring of deformations and geodetic works.

Research results and their discussion. The conducted structured narrative analysis of 86 scientific and official sources proved that the modern development of global navigation satellite systems (GNSS) is characterized by a transition from the use of separate satellite positioning technologies to complex multi-system and multi-frequency solutions. The main areas of development are the improvement of Real-Time Kinematic (RTK), Network RTK (NRTK), Precise Point Positioning (PPP) and PPP-RTK technologies, the spread of State Space Representation (SSR) corrections,

the implementation of high-precision positioning services, in particular Galileo High Accuracy Service (HAS), as well as the integration of GNSS with inertial navigation systems (INS), geoinformation technologies, unmanned aerial vehicles, LiDAR and machine learning methods.

Comparative analysis showed that RTK, NRTK, PPP and PPP-RTK technologies have different fields of application, which are determined by requirements for accuracy, time of obtaining a coordinate solution, spatial coverage, availability of reference infrastructure and correction transmission channels. RTK provides operational high-precision positioning for local geodetic works, however depends on the presence of a base station and the transmission stability of differential corrections. NRTK expands RTK's capabilities by using a network of permanent reference stations, providing high accuracy over large areas, but its efficiency is determined by the quality of the network and telecommunications infrastructure.

Unlike RTK and NRTK, PPP technology provides high-precision positioning without binding to a local base station, although it is characterized by longer convergence times. PPP-RTK combines the advantages of PPP with the ability to obtain a high-precision coordinate solution faster thanks to the use of additional satellite and atmospheric corrections, which makes it one of the most promising directions for the development of high-precision positioning.

To summarize the results of the comparative analysis, an analytical matrix of the main technologies of high-precision GNSS positioning was formed.

Criteria	RTK	Network RTK (NRTK)	PPP	PPP-RTK
Positioning principle	Relative positioning relative to the base station	Network relative positioning	Absolute high-precision positioning	Absolute positioning with high-precision corrections
The main type of corrections	Differential corrections	Network corrections and error models	Precise orbits and satellite clocks	Precise orbits, clocks, atmospheric and additional

				corrections
Spatial coverage	Local	Regional	Global or broad regional	Regional or broad regional
Base station requirement	High	A network of stations is used	No immediate proximity is required	No immediate proximity is required
Time to get a high-precision solution	Short under favorable conditions	Short in the availability of corrections	Relatively long convergence time	Abbreviated from traditional PPP
Work in real time	Yes	Yes	Possible with appropriate implementation	Yes, in the presence of operative corrections
Dependence on telecommunications	High	High	Depends on the method of obtaining corrections	High in real time
Main advantage	High efficiency	High accuracy within network coverage	Large coverage area	Combination of wide coverage and fast convergence
Main limitation	Local application zone	Dependence on the network of stations and communication	Long convergence	Difficulty of forming and delivering corrections

Comparative analysis showed that the accuracy of GNSS technologies is not a constant value and depends on the observation conditions. The centimeter or millimeter level of accuracy is determined by the characteristics of the GNSS receiver, the geometry of the satellite constellation, the number of frequencies used, the duration of observations, atmospheric conditions, the multipath of signals, the quality of corrections and the method of data processing. It is therefore appropriate to compare the results of the various studies only taking into account the experimental conditions and the statistical criteria applied.

For operational geodetic works, RTK and NRTK provide a fast acquisition of a high-precision coordinate solution, while PPP is effective for long-term observations

without the need for a local base station. PPP-RTK technology combines the advantages of wide spatial coverage with the possibility of reducing convergence time. Consequently, the choice of technology should be based on a comprehensive assessment of accuracy, time of obtaining the result, availability of infrastructure and conditions for conducting observations.

Analysis of the development of multi-system and multi-frequency GNSS technologies proved that the simultaneous use of GPS, Galileo, BeiDou and GLONASS increases the availability of satellite observations, improves the geometry of the satellite constellation and the reliability of positioning, especially in the conditions of urban development and difficult terrain. The use of multi-frequency signals also contributes to more effective elimination of ionospheric errors and acceleration of the resolution of phase ambiguities.

It was established that SSR corrections are one of the promising directions for the development of high-precision positioning, as they ensure the transmission of individual components of GNSS solution errors and create opportunities for scaling accurate positioning over large areas. A promising example of the implementation of such an approach is the Galileo High Accuracy Service (HAS), which expands the availability of high-precision corrections without necessarily using a local reference network. At the same time, the effectiveness of HAS depends on the compatibility of equipment, the quality of signal reception and the availability of corrections, so it is advisable to consider this service as a supplement to RTK and NRTK, and not their complete replacement.

Conclusions and prospects. As a result of the structured narrative analysis of scientific publications and official documentation, it was established that the effectiveness of the use of modern technologies of high-precision GNSS positioning is determined by a complex of technical and organizational factors, among which the requirements for accuracy, efficiency of obtaining coordinates, availability of reference infrastructure and conditions for performing geodetic works are of key importance. RTK, Network RTK (NRTK), Precise Point Positioning (PPP) and PPP-RTK technologies are justified to have different areas of effective application: RTK

and NRTK are the most suitable for operational local measurements, while PPP and PPP-RTK provide prospects for high-precision positioning in significant areas with less dependence on local networks of base stations. It was established that achieving centimeter or millimeter accuracy of GNSS measurements is possible only if the specified observation conditions are met, and the characteristics of the receiving equipment, the geometry of the satellite group, the duration of observations, atmospheric influences and the quality of the applied corrections have a decisive influence on the final accuracy. It was determined that the use of multi-system and multi-frequency GNSS receivers is one of the main directions of increasing the efficiency of satellite geodesy, as it provides an improvement in the availability of satellite observations, the reliability of coordinate determinations and a reduction in the time of obtaining a fixed solution. It was also established that the implementation of SSR corrections and the Galileo High Accuracy Service (HAS) is a promising direction for the development of global high-precision positioning, as it expands the possibilities of scaling accurate coordinate definitions and increases the availability of modern GNSS technologies without mandatory binding to local networks of reference stations.

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GNSS-ТЕХНОЛОГІЇ ТА СУПУТНИКОВА ГЕОДЕЗІЯ НОВОГО ПОКОЛІННЯ

***Анотація.** У статті представлено наративний огляд сучасних підходів до застосування глобальних навігаційних супутникових систем (GNSS) у геодезії та геопросторовому забезпеченні. Метою роботи є узагальнення сучасних технологій високоточного супутникового позиціонування та визначення перспектив їх використання в умовах цифрової трансформації геодезичної галузі. Для проведення огляду проаналізовано наукові публікації та офіційну документацію, присвячені технологіям Real-Time Kinematic (RTK), Network RTK (NRTK), Precise Point Positioning (PPP), PPP-RTK, State Space Representation (SSR), сервісу Galileo High Accuracy Service (HAS), а також інтеграції GNSS із безпілотними літальними апаратами та геоінформаційними системами. Аналіз охоплював сучасні підходи до високоточного позиціонування, використання багатосистемних і багаточастотних GNSS-спостережень, питання цілісності й автентичності навігаційних сигналів та перспективи розвитку супутникових сервісів високоточного позиціонування.*

У результаті аналізу систематизовано основні характеристики технологій RTK, NRTK, PPP та PPP-RTK за критеріями точності, часу збіжності, потреби в наземній референційній інфраструктурі, просторового охоплення та придатності до роботи в різних умовах спостережень. Встановлено, що RTK і NRTK забезпечують оперативне отримання високоточних координат за наявності доступу до референційної інфраструктури, тоді як PPP характеризується більшою незалежністю від локальних базових станцій, але потребує тривалішого часу збіжності. Технологія PPP-RTK поєднує переваги глобального покриття PPP із прискореним отриманням високоточного координатного рішення завдяки використанню додаткових корекцій. Показано, що досягнення сантиметрової або міліметрової точності залежить від характеристик приймального

обладнання, тривалості спостережень, кількості та геометрії супутників, якості корекцій і методики опрацювання даних.

Визначено, що перспективними напрямками розвитку GNSS-технологій є використання сервісу Galileo HAS, SSR-корекцій, інтеграція супутникового позиціонування з безпілотними літальними апаратами, геоінформаційними системами та іншими сенсорними технологіями, а також застосування методів машинного навчання для підвищення надійності координатних визначень. Результати дослідження можуть бути використані для вибору оптимальної технології високоточного GNSS-позиціонування залежно від вимог до точності, умов виконання геодезичних робіт і доступності референцної інфраструктури.

Ключові слова: GNSS-технології, супутникова геодезія, GPS, Galileo, GLONASS, BeiDou, RTK, Network RTK, PPP, PPP-RTK, SSR-корекції, Galileo HAS, високоточне позиціонування, геопросторові дані.