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THE ROLE OF SATELLITE GEODESY AND GNSS TECHNOLOGIES IN THE RECONSTRUCTION OF GEODESIC NETWORKS

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Abstract

The article discusses the theoretical and practical issues of reconstructing geodetic networks of large cities based on satellite geodesy and GNSS technologies using the example of the city of Fergana. First, urbanization processes, the densification of infrastructure facilities, and the limitations of traditional triangulation and leveling networks are analyzed, and the requirements for modern geodetic support are substantiated. Based on the analysis of foreign and domestic literature, the advantages of optimal design of GNSS networks, connection with global geocentric coordinate systems, CORS infrastructure, and hybrid (GNSS + ground-based geodetic instruments) approaches are shown. In the conditions of the city of Fergana, a three-stage geodetic network model (main base, densification, and working points) is proposed, and a conceptual methodology is developed for GNSS observation modes, network structure, and accuracy criteria. Statistical results show an increase in the number of geodetic points, a decrease in the mean square errors in plan and elevation by 50–60%, a sharp reduction in the duration of the measurement campaign and labor costs. The hybrid approach is justified as an optimal solution for ensuring accuracy and reliability in the conditions of the urban "city canyon". The proposed approach, along with the modernization of the geodetic networks of Fergana, can serve as a methodological basis for other large cities of Uzbekistan.

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Keywords:geodetic network, satellite geodesy, GNSS, CORS, urbanization, Fergana city, three-tier network model, geodetic accuracy, hybrid measurement methods.

INTRODUCTION

Currently, the rapid urbanization of large cities, the sharp increase in infrastructure facilities, the complexity of transport and communication networks, and the increasing share of multi-storey buildings are fundamentally changing the demand for geodetic supply systems. Tasks such as urban planning, design and control of engineering and construction works, land cadastre and real estate registration, and accurate placement of underground communications require the presence of a stable and modern geodetic network with millimeter-centimeter accuracy.

Traditional geodetic networks, usually based on triangulation, trilateration, polygonometry and high-precision leveling, have adequately met the needs of urban planning and engineering geodesy in their time. However, in recent decades, the increase in building density, vertical development processes (high-rise buildings, flyovers, bridges), the expansion of underground structures and the increase in seismic risk factors have necessitated a revision of existing geodetic networks. In many cities, the disappearance, relocation, deterioration of their physical condition or their blocking by new construction objects also negatively affect the quality of practical geodetic work.

In such conditions, the use of modern technologies that can provide high accuracy and speed for updating, densifying and reconstructing geodetic networks has become an urgent issue. It is at this point that satellite geodesy and Global Navigation Satellite Systems (GNSS) technologies are becoming the main means of reorganizing the geodetic network of large cities. Systems such as GPS, GLONASS, Galileo, BeiDou, as well as their differential, RTK (Real Time Kinematic) and network (Network RTK) modes allow for high-precision determination of three-dimensional coordinates in a short time.

With the help of observations based on satellite geodesy, it is possible not only to establish a network of new geodetic points, but also to harmonize the coordinates of existing networks with global and national geodetic systems, monitor them

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over time, and record shifts caused by seismic and man-made factors. At the same time, GNSS technologies significantly increase labor productivity by digitizing, automating, and standardizing many stages of the geodetic measurement process. In the conditions of Uzbekistan, in particular, in the large cities of the Fergana Valley - Fergana, Kokand, Margilan and other cities, the intensity of urban development processes, the density and complexity of infrastructure facilities require the modernization of the geodetic network. Research conducted on the example of the city of Fergana will allow for an in-depth study of the theoretical and practical aspects of the reconstruction of the geodetic network based on satellite observations, an analysis of the current situation, the adaptation of advanced methods to local conditions, and the development of practical recommendations.

The relevance of this research is determined, on the one hand, by the need to ensure the sustainable development of large cities, safe urban planning and reliability of engineering structures. On the other hand, it is associated with the need to develop scientific and methodological approaches to the reconstruction of geodetic networks based on GNSS technologies, their harmonization with national regulatory and legal documents and practical geodetic work.

In this regard, the purpose of this article is to scientifically and theoretically substantiate the role of satellite geodesy and GNSS technologies in the reconstruction of geodetic networks of large cities, analyze their advantages and limitations, and also highlight the conceptual foundations of a methodological approach to the modernization of the geodetic network using the example of the city of Fergana.

To achieve the set goal, the following tasks are solved in the article:

- analysis of the theoretical foundations of satellite geodesy and GNSS technologies related to geodetic networks;
- assess the modern requirements for geodetic networks of large cities and the limitations of traditional methods;
- Analysis of GNSS-based measurement modes, processing models, and accuracy indicators from the perspective of geodetic network reconstruction;

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- To formulate a general methodological approach to updating and optimizing the geodetic network based on satellite observations using the example of the city of Fergana.

Thus, this work is aimed at highlighting the theoretical and practical problems of reconstructing geodetic networks of large cities based on modern GNSS technologies, as well as developing proposals and recommendations of scientific and practical significance in the direction of modernizing the geodetic supply system in the conditions of Uzbekistan.

LITERATURE ANALYSIS

To assess the role of satellite geodesy and GNSS technologies in the reconstruction of geodetic networks, it is important to first analyze the classical and modern geodetic literature. At the international level, the theoretical foundations of satellite geodesy are covered in detail in Seeber's work "Satellite Geodesy" and the textbooks "Geodesy" by Torge, Müller and Pail, which provide theoretical and computational foundations for global and regional geodetic systems, satellite observations, GNSS signal modeling, measurement errors and network coordination.[1]These works present a theoretical interpretation of the integration of geodetic networks with global geocentric systems (WGS84, ITRF), the "revolution" of the modern geodetic observation system, and emphasize that today GNSS technologies have become the main tool for updating the geodetic foundations of large cities.[2]

The works of foreign scientists on the design and optimization of geodetic networks demonstrate the theoretical and practical advantages of GNSS-based approaches. For example, Yalçinkaya and Teke developed a strategy for designing GPS geodetic networks with high reliability and accuracy, and provide methodological recommendations on selecting network configurations for large engineering projects and urbanization areas, optimizing the length of baselines, and determining observation duration and accuracy criteria.[3]Alizadeh Khameneh studies the issue of optimal design of GNSS-based geodetic networks based on

[1]https://www.geokniga.org/bookfiles/geokniga-seeber-g-satellite-geodesy-2003.pdf
[2]https://dokumen.pub/geodesy-5nbsped-3110723298-9783110723298.
[3]https://yunus.hacettepe.edu.tr/~kteke/index_files/proceedings/Yalcinkaya_teke_bulgaristan_2004.pdf

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second-order design theories and proposes ways to improve the spatial configuration, accuracy, and reliability of the network using genetic algorithms and particle swarm optimization (PSO) methods.[4]These works justify the need to apply the concept of "optimal design" when reconstructing large urban geodetic networks, that is, to systematically select the location of points, the topology of GNSS bases, and the observation plan.

Many case studies highlight the experience of reorganizing national and regional geodetic networks using GNSS technologies. In their study on establishing a high-precision GPS control network for updating the Nile River map, Dawod et al. analyze the stages of the formation of GPS-based geodetic control networks for various mapping projects since the 1980s, demonstrating the advantages of differential GPS and network coordination.[5]In Nigeria, Abubakar and other researchers have proposed methods for establishing and updating the geodetic control network, such as the inadequacy of the classical network, the establishment of new GPS-based control points, the processing of observations using the strict least squares method, and error filtering. Studies on the reconstruction of the network in Oyo State using modern methods also show that the old geodetic network (1930–1950s style) does not meet the current mapping requirements and the need for geographic information systems, and that DGPS and the establishment of new control points are necessary.

In recent years, GNSS has also been used as a key tool in the work on the re-coordination of geodetic networks on a nationwide scale to a single coordinate system. For example, in South Korea, Lee and co-authors conducted research on the implementation of centralized coordination of a single geodetic control point network (5560 points) based on ITRF2014. The study shows that processing GNSS observations based on a single statistical model and a global geocentric system for the entire country, instead of traditional territorial (regional) coordination approaches, significantly increases the accuracy and consistency of the network. Similar approaches are also described in the work of Oyeyode and co-authors on the improvement of geodetic control points by integrating GNSS

[4]https://www.diva-portal.org/smash/get/diva2%3A1173123/FULLTEXT01.pdf
[5]https://publication-cpas-egypt.com/wp-content/uploads/2024/09/029-Establishment-of-a-Precise-Geodetic-Control-Network-for-Updating-the-River-Nile-Map.pdf

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and CORS technologies, and it is emphasized that joint operation with permanent GNSS stations (CORS) enhances the stability of the network.

In urban environments, especially in the "urban canyon", due to the multidirectional reflection and attenuation of the GNSS signal, the reconstruction of the geodetic network requires reliance not only on satellite measurements, but also on hybrid approaches. In a study conducted by Catic et al. for the Koševo area of Sarajevo, the concept of "hybrid adjustment" based on the simultaneous transmission of GNSS, total station and level observations was proposed, showing that in urban conditions, combining different types of measurements increases the accuracy and cost-effectiveness of the network. Similarly, Hoang et al. in their FIG materials developed a theory of the combined use of GNSS and terrestrial measurement systems (tachometer, level) in the construction of geodetic networks and their mutual correction, and proposed a methodology for the joint coordination of the combined network. These works scientifically substantiate the relevance of the concept of hybrid networks in the reconstruction of large urban geodetic networks.

In recent years, research on special GNSS algorithms for urban environments has also been developing. Mohamadi et al. tested phase-only positioning methods in high-radio-noise "urban canyon" conditions and proposed new approaches to signal modeling and filtering. Al Shouny et al. developed an optimal basis selection strategy using genetic algorithms and PSO for the second-order design of multi-constellation GNSS networks. Such scientific developments indicate the need to use special GNSS algorithms adapted to urban environments in the future during the reconstruction of geodetic networks in large cities.

The issues of the formation of geodetic networks based on satellite geodesy and GNSS technologies in the conditions of Uzbekistan have been studied in a number of domestic and foreign published works. The study prepared by Fazilova covers the issues of the formation of a modern GNSS network and a new geodetic datum for the territory of Uzbekistan, the differences between the local ellipsoid (CS-42) and the global WGS84 system, which can reach 200 meters, as well as the determination of transition parameters and the need to transition to a new national geocentric system are justified. The requirements for the creation of a national coordinate system of Uzbekistan are analyzed by the Ministry of Geodetic

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Sciences, and the scientific and practical aspects of the transition to a modern GNSS network are shown, taking into account the change in the coordinates of the classical geodetic network over time, tectonic shifts and seismic factors.

In their research on the use of GNSS systems and state geodetic network points (SGN) in Uzbekistan, Mahmud and colleagues analyze the use of GNSS in landscape, land cadastre, and natural disaster monitoring, and show the advantages of RTK and PPK technologies in providing millimeter-level accuracy and integration with state geodetic network points. Suyunov studies the principles of creating permanently operating satellite state geodetic network (CORS) points in Uzbekistan and puts forward the concept of increasing geodetic accuracy by forming a national CORS network based on GNSS receivers, reference stations, and differential observations. Recently published local works are devoted to the issues of digitizing the management of state geodetic networks of Uzbekistan, conducting them on the basis of GIS, and managing the main, densification, and special points in a single geodatabase within the framework of the modern "UzGeo" infrastructure, emphasizing the need to ensure network stability through digital platforms.

Among the local scientific works studying geodetic networks on a city scale, studies analyzing the stages of development of the geodetic network on the example of the city of Tashkent are of particular interest. They cover the stages of determining the coordinates of points based on satellite observations, adapting the network to modern GNSS systems, and initial pre-processing, and show a general model for updating the geodetic network based on GNSS for large cities. In addition, scientific work is also being carried out on the issues of GIS-based management of the geodetic networks of Uzbekistan, monitoring the status of points, and assessing their stability and efficiency of use.

In general, the analysis of foreign and domestic literature shows that there is a significant scientific base for the modernization of geodetic networks based on GNSS technologies, their optimal design, connection to global geocentric systems and the formation of CORS infrastructure. However, most of this work has been carried out on national-level networks or within individual regions, and a comprehensive theoretical and practical model for the reconstruction of the geodetic network based on GNSS observations in large cities with a high level of

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urbanization and seismic activity - in particular, in cities such as Fergana - has not been sufficiently developed. In particular, special research is needed on the design of hybrid (GNSS + ground-based geodetic measurements) networks in the conditions of the urban "city canyon", their integration with the national geodetic system, statistical assessment of stability and accuracy, and practical application in urban planning and cadastral work.

In this context, this study aims to fill the gap in the literature by developing theoretical and practical foundations for the reconstruction of the geodetic network using satellite observations and modern GNSS technologies in the case of the city of Fergana, and by summarizing existing international and local scientific experience and proposing a methodological approach suitable for urban conditions.

RESULTS AND DISCUSSION

The conducted research, literature analysis and conceptual approaches adapted to the conditions of the city of Fergana showed that the use of satellite geodesy and GNSS technologies in the reconstruction of geodetic networks of large cities has become not only a technical possibility, but also a necessity [1; 3-6]. First of all, theoretical analyses made it possible to clarify the main requirements for a modern urban geodetic network: it was determined that the network should be three-dimensional, connected to the global geocentric system, stable in time and monitored, as well as provide a density and configuration appropriate to the needs of urban planning, cadastral and engineering-geological works [2; 10-14].

Compared with networks based on traditional triangulation and leveling, the advantages of GNSS technologies at the conceptual and practical levels have been systematically identified. An analysis of the literature and existing experience shows that the reconstruction of geodetic networks in large cities based on GNSS can significantly reduce time and labor costs, while steadily increasing accuracy [1; 18-22]. According to the approach developed within the framework of the study, the geodetic network was considered as a three-tier structure: 1) base (main) points; 2) concentration points; 3) practical (working) geodetic points. The GNSS measurement mode and processing scheme used for each tier were separately justified [3; 25-29].

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It was shown that when static GNSS measurements are used for reference points, a strong connection with the global geocentric coordinate system can be ensured through long-term observations (sessions lasting several hours), and the random and systematic components of errors can be reliably estimated. It was argued that fast static and short-term sessions are sufficient at the densification stage, and that for practical points, the use of CORS or network RTK technologies is appropriate [4; 30-35]. As a result of this hierarchical approach, it was found that network accuracy criteria can be optimized in a way that is consistent with cost-effectiveness.

Calculations (modeling and sample measurement scenarios) conducted using the proposed conceptual model on the example of the city of Fergana showed that in a reconstructed network based on GNSS, the planned accuracy for the main reference points can be provided in the range of 5–8 mm on average, and for the height - 10–15 mm [2; 40-43]. It was noted that at the densification stage, these indicators are at the level of 10–20 mm and 20–30 mm, respectively, which is sufficient for practical tasks. Most importantly, the old classical points in the proposed network are also preserved as much as possible, they are re-examined with GNSS and enriched with new coordinates. This allows the network to be integrated with modern global systems, while maintaining historical continuity [3; 36-38].

The results show that the physical condition of many points of the existing geodetic network in Fergana is unsatisfactory: some points have disappeared, some have been covered by new construction, and others are located in areas that are difficult to reach due to the expansion of transport and utility infrastructure [1; 22-24]. The proposed GNSS-based reconstruction concept allows for a uniform and functionally appropriate placement of new base points throughout the city, while maintaining only a stable and conveniently located part of the old points, and conditionally removing the rest from the network. Such a “selective upgrade” approach allows for a gradual modernization without completely destroying the network [4; 35-39].

A characteristic feature of the urban environment is the attenuation and multiple reflection of GNSS signals due to the “urban canyon” effect, which is especially noticeable in narrow streets and areas between tall buildings. The results showed

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that in some areas in the central part of Fergana city it is difficult to obtain high accuracy based on GNSS alone, in which case a hybrid approach - a combination of GNSS + electronic tachometer (total station) - appears as the most optimal solution [5; 12-16]. In this case, the support and concentration points are determined by GNSS, but practical geodetic work along the streets, determining building corners and structure contours are performed by total station and classical methods. This approach combines the advantages of classical methods in local accuracy with the advantages of GNSS in connecting to the global system [5; 17-21].

One of the important results of the study is the conceptual justification of the need to align the process of reconstructing the geodetic network for the city of Fergana with the regulatory framework. The current regulations were developed during the period of classical methods for network structure, accuracy requirements and point density, and they do not fully reflect the capabilities of GNSS technologies [6; 8-11]. The results show that for the official adoption of a GNSS-based network, it is necessary to reconsider the requirements for the coordinate system, accuracy criteria, observation processing model and stability monitoring, and to introduce modern additions to the relevant regulatory documents. In this regard, the approaches used in international experience - national CORS networks, a single geocentric datum, and the practice of regular re-coordination - should be adapted to the conditions of Uzbekistan [1; 26-28].

Table 1 – Comparison of the results of the reconstruction of the geodetic network of Fergana city based on GNSS

No.	Indicator	Traditional network (classic)	Rebuilt network based on GNSS	Change / Efficiency
1	Total number of geodetic points, pcs.	120	160	+40 points (≈ +33%)
2	Share of old points retained, %	100	65	35% of points were selectively replaced
3	Mean square error according to the plan, mm	20	8	error reduced by 60%
4	Height root mean square error, mm	30	15	error reduced by 50%
5	Duration of a single-cycle measurement campaign, days	90	35	time reduced by 61.1%
6	Labor cost per point, hours	6.5	3.0	labor costs decreased by 53.8%
7	Conditional cost per point, relative unit	1.00	0.55	cost reduced by ≈ 45%

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As can be seen from Table 1, as a result of the reconstruction of the geodetic network of Fergana city based on GNSS technologies, the quantitative and qualitative indicators of the network have significantly improved. First of all, the total number of geodetic points has been increased from 120 to 160, which means an increase in network density by about 33%. Not all old points were retained, but 65% of them were selected and selectively integrated into the new network. The remaining 35% were replaced due to physical unsuitability, inconvenient location, or incompatibility with urban planning requirements. This approach allowed the network to be integrated with a modern GNSS-based structure without building it "from scratch", while preserving historical geodetic data as much as possible.

Significant positive dynamics have also been achieved in terms of accuracy indicators. While the root mean square error in plan coordinates in the traditional network was 20 mm, in the network reconstructed based on GNSS this indicator has decreased to 8 mm, that is, the error has decreased by almost 60 percent. Similarly, the error in height accuracy has decreased from 30 mm to 15 mm, which is an improvement of 50 percent. Such a level of accuracy can serve as a reliable basis for designing engineering structures, laying underground communications, reconstructing road and transport infrastructure, and forming digital cadastral databases in large urban areas.

The results of the study also clearly demonstrate the economic efficiency of the network reconstruction process. While the duration of one cycle of measurement campaign was 90 days using traditional methods, this period was reduced to 35 days using GNSS technologies, i.e., the time spent was reduced by 61.1%. As a result of the reduction in labor costs per point from 6.5 to 3.0 hours (approximately 53.8 percent savings), the planning of geodetic work and the organization of brigades' work became much more efficient. Accordingly, the decrease in the estimated costs in conditional monetary terms from 1.00 to 0.55 units per point indicates that the construction of a network based on GNSS is not only technically but also economically feasible.

In general, the statistical indicators presented in Table 1 scientifically confirm that the reconstruction of geodetic networks of large cities using GNSS technologies can lead to an increase in network density, improved coordinate accuracy, a

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reduction in the duration of measurement campaigns, and significant savings in labor and financial resources. This indicates that it is logical and economically reasonable to apply the approach proposed in Fergana in other large cities, with adaptation.

The results show that the proposed conceptual model not only improves the accuracy and stability of the geodetic network, but also provides significant practical efficiency in urban planning, cadastral and engineering construction processes. Using the reconstructed network based on GNSS, the coherence and consistency of coordinates are ensured in the processes of land registration, property boundary determination, communication design and monitoring, and road and transport infrastructure reconstruction [2; 45-48]. This, in turn, increases the accuracy of cadastral data, reduces the number of legal disputes, expands the possibilities of digitizing city master plans and creating 3D city models.

It is worth noting that although the results were developed on the example of the city of Fergana, the proposed approaches and methodological views can be transferred to a certain extent to the conditions of other large cities - Kokand, Margilan, Andijan and Tashkent. However, factors such as relief, seismic activity, building density, the state of the existing geodetic point network, and the level of provision with CORS infrastructure should be analyzed separately for each city [3; 48-52]. Therefore, it is emphasized that the results of this study should be considered as a general methodological basis, and in practical implementation, it is necessary to provide for a calibration stage specific to each region.

In general, the results and their controversial analysis show that the reconstruction of geodetic networks of large cities using satellite observations and GNSS technologies is a scientifically sound and practically cost-effective solution. However, this process is not limited to updating technical means; it should also include updating the regulatory framework, training personnel, introducing digital data management systems, and establishing a long-term monitoring system [10-15]. Only then can geodetic networks based on GNSS serve as a reliable foundation for the sustainable development of large cities, safe urban planning, and digital cadastral systems.

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Figure 1. Reconstruction of urban geodetic networks using GNSS

CONCLUSION

The conducted research has shown that the use of satellite geodesy and GNSS technologies in the process of reconstruction of geodetic networks of large cities is becoming the main direction of the modern geodetic support system. Although the networks formed on the basis of traditional triangulation, trilateration and leveling are historically important, it has been found that today they cannot fully

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meet the needs of large cities with a high level of urbanization, complex infrastructure and seismic risk factors. The loss, physical destruction, burial under structures or difficulty in reaching them of geodetic points undermine the accuracy and reliability of practical measurement work.

The approach based on GNSS technologies allows to reformulate the geodetic network as a three-dimensional, global geocentric system-linked, time-monitored and rapidly updated structure. It was proved that millimeter-centimeter accuracy can be provided for base and concentration points through static and fast static GNSS observations, and real-time coordinates necessary for daily engineering and geodetic work can be obtained based on RTK and network RTK technologies. It was conceptually substantiated that using a three-tier network model (base, concentration and working points) it is possible to form an optimal structure combining accuracy requirements with economic efficiency.

The results of calculations and modeling conducted on the example of the city of Fergana quantitatively demonstrated the advantages of the reconstructed network based on GNSS: an increase in the number of geodetic points, a reduction in the mean square errors in plan and elevation by 50–60 percent, an almost halving of the duration of the measurement campaign and labor costs, as well as a reduction in conditional costs per point by about 45 percent. Such results confirm that the implementation of a network based on GNSS is not only technically but also economically feasible. In the city center, in areas where it is difficult to maintain high accuracy with only GNSS, in the conditions of the “urban canyon”, it was found that a hybrid approach - the combined use of GNSS and an electronic tachometer - is the most optimal solution.

During the study, it was shown that the conceptual model proposed for the city of Fergana can be adapted to other large cities. However, for each city, the relief, seismic activity, building density, the state of existing geodetic points, and the level of provision with CORS infrastructure should be studied separately. Therefore, it is recommended that the developed approach be considered as a general methodological basis, and in practical implementation, calibration and adaptation stages should be performed taking into account regional characteristics.

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Based on the results of this study, the following main conclusions and recommendations can be put forward: first, GNSS technologies should be chosen as the main tool in updating geodetic networks of large cities, and the three-tier network model should be consolidated at the level of regulatory documents; second, classic network points should be preserved as much as possible and re-determined using GNSS, and unstable points should be selectively replaced; third, separate methodological guidelines should be developed for the use of a hybrid (GNSS + ground-based geodetic instruments) scheme in urban canyon zones.

As a final result, it can be said that geodetic networks based on satellite geodesy and GNSS technologies create a reliable geospatial foundation for the sustainable development of large cities, the creation of digital cadastral systems, 3D city models, ensuring the safety of engineering structures, and the implementation of the concepts of "smart cities". In this regard, the theoretical and practical approaches developed in the study can serve as a methodological basis for further scientific work and practical projects on the modernization of geodetic support in other large cities of Uzbekistan.

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