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Formation and accuracy assessment of a GNSS/GIS basis for geodynamic monitoring of Almaty city

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Abstract: Almaty is located in the seismically active zone of the Northern Tien Shan, where the development of engineering, transport, and underground infrastructure requires a reliable geodetic basis for regular control of the spatial position of the ground surface and engineering facilities. The aim of this study is to establish an initial GNSS/GIS basis for subsequent geodynamic monitoring of Almaty and to assess the accuracy of coordinate solutions obtained from one campaign of static GNSS observations. The study uses a GNSS network consisting of the reference station ALMA and the observation points CHIL, ESIK, FABR, and KGAI. The observations were processed in the South Geomatics Office software package using GPS, GLONASS, and BeiDou signals. The results of the three-dimensional network adjustment show that the root mean square errors of the observation points range from 0.004 to 0.010 m, confirming the suitability of the network for high-precision geodetic observations. The GIS component is presented as a spatial framework for mapping the GNSS network and for subsequent comparison of repeated measurements with a digital elevation model, fault zones, engineering-geological conditions, urban density, and infrastructure objects. Since the study is based on one observation epoch, it does not calculate actual displacement vectors or deformation rates. The scientific contribution of the study lies in clarifying the methodological role of a high-precision GNSS/GIS basis as the first stage of a long-term geodynamic monitoring system for the urbanized and seismically active territory of Almaty. Future research should include repeated GNSS observation campaigns, continuous monitoring stations, and the integration of InSAR and geological datasets to quantify deformation rates, improve seismic hazard assessment, support infrastructure resilience, and enhance evidence-based urban planning and disaster risk management in Almaty.

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1 Introduction

The current development of satellite geodesy and geoinformation technologies has significantly expanded the possibilities for studying deformation processes in seismically active and urbanized territories. For large cities located in mountainous and foothill regions, spatial control of the ground surface has both scientific and applied importance. High population density, the concentration of engineering structures, transport facilities, underground infrastructure, and high-rise buildings increase the requirements for the accuracy of geodetic observations and for the interpretation of coordinate data. In international practice, Global Navigation Satellite Systems (GNSS) are regarded as one of the key tools for recording modern ground movements, assessing the stability of geodetic points, and constructing

coordinate time series (Bock & Melgar, 2016; Hofmann-Wellenhof et al., 2008; Teunissen & Montenbruck, 2017).

A unified reference frame and a stable geodetic basis are particularly important in such studies. Modern realizations of the International Terrestrial Reference Frame, including ITRF2020, allow station position time series, linear velocities, and nonlinear motion components to be considered, which is essential for the analysis of crustal deformation and for the comparison of results obtained in different observation epochs (Altamimi et al., 2023). In geodynamic monitoring, this means that the accuracy of a single coordinate solution is only the first stage. The reliable identification of deformation requires repeated measurement campaigns, comparable processing methods, control of systematic errors, and statistical assessment of the significance of detected displacements.

Almaty is one of the most important urbanized centers of Kazakhstan and is located within the influence zone of active tectonic structures of the Northern Tien Shan. The seismotectonic setting of the city is associated with the proximity of the Zailiysky Alatau mountain range, pronounced fault tectonics, contrasting relief, and historically known strong earthquakes. Recent studies indicate that the northern front of the Zailiysky Alatau and adjacent areas show evidence of Late Quaternary and modern tectonic activity, while buried and surface fault structures may influence the seismic risk of the urban area (Grützner et al., 2017; Amey et al., 2021). Therefore, establishing a stable geodetic basis for regular control of deformation processes is an urgent task for Almaty.

The seismic hazard of Almaty has been considered in studies devoted to probabilistic seismic hazard assessment, seismic microzonation, and the analysis of engineering-geological conditions. These studies emphasize that hazard assessment should take into account not only the parameters of possible seismic events, but also local soil properties, relief, building characteristics, and the degree of engineering development of the territory (Silacheva et al., 2018; Silacheva et al., 2020). Consequently, geodynamic monitoring cannot be limited to measuring the coordinates of individual points. Its results should be embedded in a spatial analysis system in which GNSS data are compared with natural and anthropogenic factors.

Geographic Information System (GIS) technologies make it possible to move from a point-based representation of GNSS observations to a spatially organized model of the territory. In a GIS environment, the coordinates of monitoring points can be linked with a digital elevation model, geological and tectonic layers, engineering-geological data, urban building density, transport corridors, and underground structures. This approach provides opportunities for cartographic visualization, spatial comparison, and preliminary identification of areas that require more detailed control (Zaczek-Peplinska et al., 2025). For Almaty, this task is especially relevant because the city includes plain, foothill, and slope areas that differ in terms of ground-surface stability.

In recent years, combined approaches involving GNSS, GIS, and Earth observation methods have increasingly been used to study deformations in urbanized territories. For example, research on Almaty and its surroundings based on Sentinel-1 and SBAS-InSAR data has shown the possibility of identifying spatial patterns of ground movement and comparing them with faults, tectonic boundaries, and urban infrastructure (Bayramov et al., 2024). However, InSAR results require independent ground validation. In this respect, GNSS networks can serve as a reference basis for verifying remote sensing data and for forming long-term series of high-precision coordinates.

At the same time, it is necessary to clearly distinguish between the establishment of a geodetic basis and geodynamic monitoring itself. A single campaign of static GNSS observations makes it possible to determine point coordinates, assess adjustment accuracy, and form the initial observation epoch. However, such a campaign does not allow actual displacement vectors, horizontal and vertical deformation rates, or temporal trends to be calculated independently. For this purpose, at least two, and preferably several, repeated campaigns conducted according to a unified methodology are required. This methodological distinction is important because, without it, conclusions about geodynamic processes may be broader than the available data allow.

The initial manuscript was focused on the integration of GNSS and GIS technologies in the geodynamic monitoring system of Almaty. However, the joint use of GNSS and GIS cannot itself be treated as a new scientific idea because this approach is widely used in modern geodesy and geoinformation analysis. Therefore, the scientific contribution of the revised article has been clarified. It consists of establishing an initial GNSS/GIS basis for Almaty, assessing the accuracy of coordinate solutions at five points of the observation network, and developing the logic of further use of this basis for repeated measurements, displacement calculation, and spatial interpretation of deformation processes.

Thus, the research problem is that the conditions of Almaty require not only a high-precision GNSS network, but also a methodologically correct scheme for its inclusion in a GIS-oriented system of long-term geodynamic monitoring. This scheme should account for the limitations of a single observation epoch and define the subsequent stages required for calculating real displacements and deformation rates.

The aim of the study is to establish and assess the accuracy of a GNSS/GIS basis for subsequent geodynamic monitoring of Almaty city. To achieve this aim, the following tasks were addressed: an observation GNSS network consisting of the ALMA reference station and the CHIL, ESIK, FABR, and KGAI points was formed; static GNSS observations were processed; a three-dimensional adjustment of the network was performed; coordinate accuracy was assessed using RMS and RMSE indicators; the GIS component was described as a spatial basis for further comparison of GNSS data with natural and anthropogenic factors; and methodological limitations related to the absence of repeated measurement epochs were identified.

2 Materials and methods

The study was carried out in the territory of Almaty and the adjacent foothill areas of the Northern Tien Shan. This territory is characterized by a complex tectonic structure, pronounced relief heterogeneity, high seismicity, and intensive development of urban infrastructure. These conditions determine the need to establish a stable geodetic basis for regular monitoring of the spatial position of observation points.

When interpreting the results, it is necessary to consider that potential deformation processes in Almaty may be associated with both natural and technogenic factors. Natural factors include tectonic activity, relief conditions, seismic impacts, and engineering-geological features. Technogenic factors include dense urban development, high-rise construction, the development of transport networks, the operation of underground structures, and local changes in hydrogeological and ground conditions.

The study used a GNSS network consisting of one reference station, ALMA, and four observation points, CHIL, ESIK, FABR, and KGAI. The ALMA station was adopted as the fixed initial station with known coordinates. The remaining points were used to assess the spatial configuration of the network, the quality of the baselines, and the accuracy of the coordinate solutions.

The observation points were selected to cover different parts of the study area and to ensure the geometric stability of the network. The presence of baselines of different lengths increases the reliability of the adjustment and makes it possible to control the effect of random measurement errors. Since the original observation logs were not available to the corresponding author, the exact dates of the field measurements, receiver models, antenna models, and individual session parameters should be verified by the authors before final archive submission.

Static GNSS observations were performed using dual-frequency multi-constellation GNSS receivers capable of tracking GPS, GLONASS, and BeiDou signals. The observations were carried out in static mode, which corresponds to the tasks of high-precision coordinate determination and subsequent use of the points as a reference basis for geodynamic monitoring. The methodological foundations of such work are consistent with general principles of GNSS geodesy and post-processing of satellite observations (Hofmann-Wellenhof et al., 2008; Teunissen & Montenbruck, 2017; Orynbasarova et al., 2023).

The initial observation data were recorded in RINEX format and processed in the South Geomatics Office software package. The processing workflow included project creation, definition of the WGS 84/ITRF2020 coordinate system, import of observation files, control of data quality, baseline processing,

ambiguity resolution, network consistency checks, and three-dimensional adjustment. Similar GNSS network adjustment and quality-control principles are widely used in engineering-geodetic and geodynamic applications (Gargula, 2011; Karpic et al., 2022; Karpic et al., 2023).

Quality control of the initial observations included analysis of satellite geometry, sky plot distribution, signal-to-noise ratio, multipath effects, and the stability of phase measurements. Observations with low signal quality were excluded from further processing. Particular attention was paid to the correctness of integer ambiguity resolution, since the fixed ambiguity solution is one of the main indicators of the reliability of carrier-phase processing.

The quality of the baseline solutions was assessed using RMS and ratio parameters. Solutions with RMS below 30 mm and ratio not less than 3 were considered acceptable. After baseline processing, network consistency was checked, residual errors were analyzed, and a three-dimensional least-squares adjustment was performed. The resulting coordinates were then used as the initial coordinate basis for subsequent GIS visualization and interpretation.

The GIS component of the study is intended for spatial systematization and interpretation of GNSS results. In the current revision, it is considered as a preparatory spatial framework rather than as a complete hazard-zonation model. This distinction is important because the available data consist of one GNSS observation epoch and therefore do not yet allow the construction of full displacement fields.

The recommended structure of the subsequent GIS database includes the following layers: GNSS observation points, network baselines, a digital elevation model, tectonic and fault structures, engineering-geological conditions, transport and underground infrastructure, urban building density, and areas of potential geodynamic risk. In the future, such layers will make it possible to compare GNSS-derived displacements with factors controlling the stability of the urbanized territory.

At this stage, the GIS analysis performs two functions. The first function is cartographic representation of the network configuration and spatial relationships between points. The second function is preparation of the methodological basis for future spatial comparison. After repeated GNSS campaigns are conducted, the GIS environment will allow maps of displacement vectors, deformation rates, and priority zones for geodetic control to be created.

Because the current study presents one observation epoch, actual displacements and deformation rates were not calculated. For subsequent stages of monitoring, the following computational scheme is proposed. Horizontal and vertical displacements between two epochs are determined as coordinate differences: $\Delta E = E_2 - E_1$, $\Delta N = N_2 - N_1$, and $\Delta H = H_2 - H_1$. The horizontal displacement magnitude is calculated as $D = \sqrt{(\Delta E)^2 + (\Delta N)^2}$. Displacement rates are determined as the ratio of displacement to the time interval between observation epochs: $V_E = \Delta E / \Delta t$, $V_N = \Delta N / \Delta t$, and $V_H = \Delta H / \Delta t$.

The statistical significance of the displacement should be assessed by considering the combined uncertainty of two observation epochs: $\sigma_{\Delta} = \sqrt{(\sigma_1^2 + \sigma_2^2)}$. A displacement can be interpreted as statistically significant only when its value exceeds the selected confidence threshold. Such an approach makes it possible to avoid overinterpretation of random coordinate fluctuations as real geodynamic deformation.

3 Results

As a result of the revision, the general methodological scheme of the study was clarified. The GNSS block provides high-precision coordinate determination of the observation points and the formation of an initial coordinate epoch. The GIS block provides spatial organization of the obtained results, cartographic visualization, and preparation for subsequent comparison with natural and anthropogenic factors.

The integration of these two blocks is intended for future analysis of displacement fields, deformation rates, and zones requiring priority control. In the present study, the practical result is not a completed geodynamic zoning map, but a verified initial coordinate and spatial basis for long-term monitoring (Figure 1).

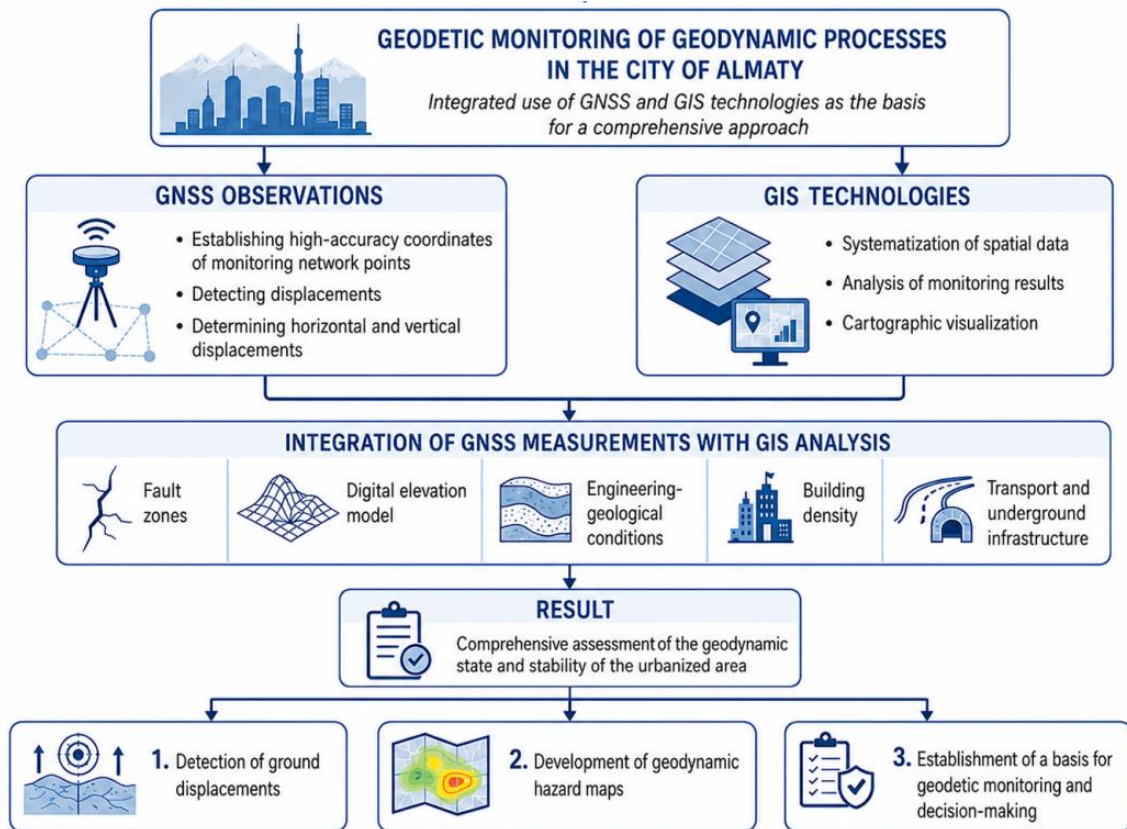


Figure 1. Methodological scheme for integrating GNSS and GIS technologies in the geodetic monitoring of geodynamic processes in Almaty. *Source: compiled by the authors*

The GNSS network consists of the ALMA reference station and the CHIL, ESIK, FABR, and KGAI observation points (Figure 2). The ALMA station was used as the fixed initial point during adjustment. This explains the zero RMS and RMSE values for ALMA. Therefore, the ALMA values should not be interpreted as an independent accuracy estimate, but rather as a consequence of its status as the fixed control point.

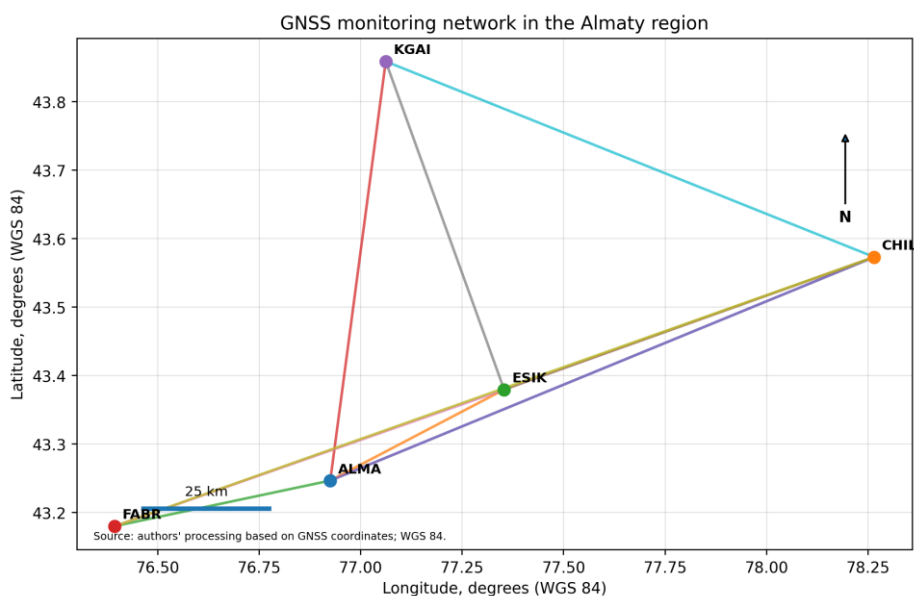


Figure 2. GNSS monitoring network, including the ALMA reference station and the CHIL, ESIK, FABR, and KGAI observation points. *Source: authors' processing based on GNSS coordinates in WGS 84.*

The network configuration provides the initial coordinate basis for subsequent repeated GNSS campaigns. The obtained coordinates can be used as the first observation epoch, relative to which future displacements, displacement vectors, and deformation rates can be calculated.

The results of the three-dimensional adjustment are presented in Table 1. The station coordinates are given in the spatial X, Y, and Z coordinate system. RMS and RMSE indicators obtained during the processing in South Geomatics Office are also provided for each station.

Table 1. Results of the 3D adjustment of the GNSS network in the spatial coordinate system

Station	X, m	Y, m	Z, m	RMS, m	RMSE_X, m	RMSE_Y, m
ALMA	1052765.268	4533187.935	4348007.129	0.000	0.000	0.000
CHIL	941381.750	4532011.170	4374236.020	0.006	0.002	0.004
ESIK	1016628.710	4531019.831	4358735.673	0.010	0.003	0.007
FABR	1095957.369	4528248.252	4342694.948	0.004	0.002	0.003
KGAI	1031402.321	4489757.831	4397096.542	0.005	0.002	0.003

Note. ALMA was used as the fixed reference station. The zero RMS and RMSE values for ALMA are the result of the adjustment constraint. Coordinates and accuracy indicators are based on the authors' processing in South Geomatics Office.

The lowest RMS value among the observation points was obtained for FABR and equals 0.004 m. The highest RMS value was obtained for ESIK and equals 0.010 m. The RMS values for CHIL and KGAI are 0.006 m and 0.005 m, respectively. These results indicate centimeter-level accuracy of the coordinate solutions and confirm the suitability of the network as an initial geodetic basis for repeated observations.

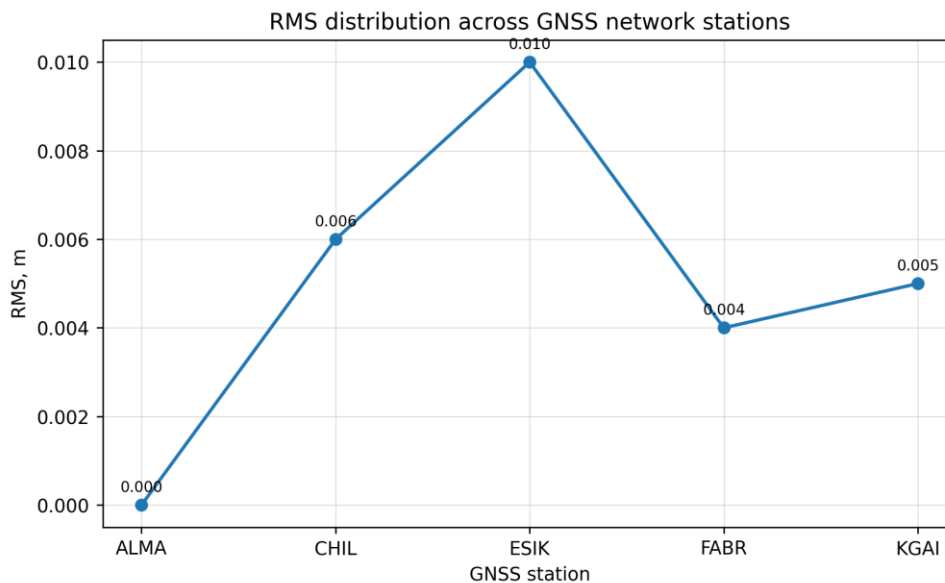


Figure 3. RMS distribution across the GNSS network stations. Source: authors' processing based on the results of the 3D network adjustment

The GIS component of the study was structured as a basis for spatial analysis of GNSS data. In the current version, it includes the placement of GNSS points on a coordinate-based map and the preparation of a spatial-data logic for subsequent comparison with natural and anthropogenic factors.

The most important factors for subsequent analysis are the proximity of GNSS points to tectonic and fault structures, the elevation and slope characteristics derived from a digital elevation model, engineering-geological conditions, urban density, the presence of transport and underground infrastructure, and zones of deformation previously identified using remote sensing or engineering surveys.

The prepared GIS structure makes it possible to move from a point-based representation of GNSS measurements to the spatial interpretation of monitoring results. However, in the present study, GIS analysis is not used for final geodynamic hazard zoning because such zoning requires repeated measurements, calculation of displacement vectors, and comparison with independent data, including InSAR, engineering-geological materials, and seismic monitoring results.

4 Discussion

The obtained results show that the established GNSS network provides sufficient accuracy for use as an initial coordinate basis. RMS values from 0.004 to 0.010 m correspond to the accuracy level required for high-precision geodetic work and for subsequent monitoring of changes in the position of points. This is an important practical result because future displacements cannot be reliably estimated without a stable initial network.

At the same time, the results of one observation campaign do not allow conclusions to be drawn about actual modern deformations of the ground surface. Full geodynamic monitoring requires repeated GNSS campaigns carried out according to a unified methodology, in the same reference frame, and under comparable observation conditions (Hamit et al., 2025). Only with two or more epochs is it possible to determine horizontal and vertical displacements, calculate deformation rates, and assess their statistical significance (Bock & Melgar, 2016; Altamimi et al., 2023).

Comparison with recent studies shows that, for the territory of Almaty, it is especially important to combine GNSS observations with remote sensing and GIS methods. SBAS-InSAR studies of Almaty demonstrate the possibility of identifying spatial patterns of deformation and their relationships with faults and urban infrastructure (Bayramov et al., 2024). However, InSAR results require ground validation. In this respect, the ALMA-CHIL-ESIK-FABR-KGAI GNSS network can be used as a reference basis for verifying and refining remote sensing results.

One limitation of the study is the small number of observation points. A five-station network makes it possible to establish an initial coordinate basis, but it is insufficient for a complete assessment of the geodynamic state of the entire Almaty agglomeration. To improve monitoring reliability, the network should be expanded by adding points near fault zones, on foothill slopes, in areas of dense urban development, and near critical infrastructure.

Another limitation is the preparatory character of the GIS component. In the present version, it performs the function of cartographic representation and data structuring. Future studies should include full GIS layers, including a digital elevation model, active faults, engineering-geological conditions, infrastructure objects, and remote sensing results. With such data, it will be possible to perform preliminary zoning of the territory according to the priority of geodynamic control.

Thus, the results of the study should be interpreted as the first stage in establishing a geodynamic monitoring system rather than as completed identification of geodynamic regularities. The scientifically correct conclusion is that a high-precision GNSS/GIS basis has been created. This basis can be used for subsequent observation cycles, calculation of actual deformation parameters, and mapping of the spatial distribution of displacements.

5 Conclusion

This study established an initial GNSS/GIS basis for subsequent geodynamic monitoring of Almaty city. The GNSS network includes the ALMA reference station and the CHIL, ESIK, FABR, and KGAI observation points. Processing of static GNSS observations and three-dimensional adjustment produced coordinate solutions with RMS values ranging from 0.004 to 0.010 m for the observation points. These results confirm the suitability of the network for high-precision geodetic observations and its use as an initial coordinate basis.

The scientific significance of the study lies in clarifying the methodological approach to forming a GNSS/GIS basis for an urbanized and seismically active territory. The practical significance is that the

obtained network can be used for subsequent repeated measurements, control of the stability of engineering-developed areas, and integration with GIS layers representing natural and anthropogenic factors.

The study also has important limitations. Based on one GNSS observation epoch, it is not possible to reliably calculate displacement vectors, deformation rates, or temporal trends. Therefore, the present study does not formulate a new geodynamic law or a completed deformation model for Almaty. The results should be considered the first stage required for organizing long-term monitoring.

Further development of the study requires repeated GNSS campaigns, calculation of horizontal and vertical displacements between epochs, mapping of displacement vectors and deformation rates, expansion of the observation network in areas of faults and dense urban development, and integration of GNSS results with InSAR data, a digital elevation model, and engineering-geological materials.

Author contributions statement:

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Gulnar Jangulova	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓		
Gulban Baidauletova	✓						✓	✓	✓	✓				
Olzhas Kurmanbayev		✓	✓	✓			✓		✓	✓	✓			
Nurzhan Khamit	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		

- C : Conceptualization
- M : Methodology
- So : Software
- Va : Validation
- Fo : Formal analysis
- I : Investigation
- R : Resources
- D : Data Curation
- O : Writing - Original Draft
- E : Writing - Review & Editing
- Vi : Visualization
- Su : Supervision
- P : Project administration
- Fu : Funding acquisition

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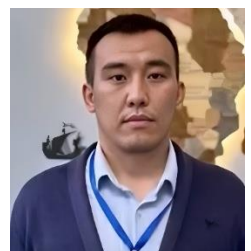
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