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Indexing in Scopus and Web of Science ensures high international visibility of publications, promotes citation growth, and reflects the editorial board's commitment to publishing relevant, original, and scientifically significant research in the fields of geology and technical sciences.

«Қазақстан Республикасы Ұлттық ғылым академиясының Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналы 2016 жылдан бастап халықаралық реферативтік және ғылымиметриялық Scopus дерекқорында индекстеледі және тұрақты библиометриялық көрсеткіштерді көрсетіп келеді.

Сонымен қатар журнал Web of Science платформасының (Clarivate Analytics, 2018) халықаралық реферативтік және наукометриялық дерекқоры Emerging Sources Citation Index (ESCI) тізіміне енгізілген.

ESCI дерекқорында индекстелуі журналдың халықаралық ғылыми рецензиялау талаптары мен редакциялық этика стандарттарына сәйкестігін растайды, сондай-ақ Clarivate Analytics компаниясы тарапынан басылмды Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) және Arts & Humanities Citation Index (AHCI) дерекқорларына енгізу қарастырылуда.

Scopus және Web of Science дерекқорларында индекстелуі жарияланымдардың халықаралық деңгейде жоғары сұранысқа ие болуын қамтамасыз етеді, олардың дәйексөз алу көрсеткіштерінің артуына ықпал етеді және редакциялық алқаның геология мен техникалық ғылымдар саласындағы өзекті, бірегей және ғылыми тұрғыдан маңызды зерттеулерді жариялауға ұмтылысын айқындайды.

Научный журнал «News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences» с 2016 года индексируется в международной реферативной и наукометрической базе данных Scopus и демонстрирует стабильные библиометрические показатели.

Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).

Индексирование в ESCI подтверждает соответствие журнала международным стандартам научного рецензирования и редакционной этики, а также рассматривается компанией Clarivate Analytics в рамках дальнейшего включения издания в Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) и Arts & Humanities Citation Index (AHCI).

Индексирование в Scopus и Web of Science обеспечивает высокую международную востребованность публикаций, способствует росту цитируемости и подтверждает стремление редакционной коллегии публиковать актуальные, оригинальные и научно значимые исследования в области геологии и технических наук.

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CONCEPT OF PROCESSING STATIC GNSS MEASUREMENTS IN GEODYNAMIC MONITORING OF ALMATY

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Abstract. *Relevance.* Geodynamic monitoring in seismically active Almaty requires a common coordinate reference framework for comparing repeated geodetic observations. Quality control of satellite measurements is essential for distinguishing potential deformation-related displacements from coordinate changes caused by observation and processing errors. *Objective.* To provide a methodological basis for processing static GNSS observations to establish a coordinate framework for geodynamic monitoring and assess the geodetic network's internal consistency. *Materials and methods.* Multiconstellation static GPS, GLONASS, and BeiDou observations collected at geodetic network stations in Almaty were processed using South Geomatics Office. Processing comprised data screening, baseline computation, phase ambiguity resolution, and three-dimensional network adjustment. Fixed-ambiguity solutions were obtained. Phase residuals, baseline solution characteristics, and RMS values were jointly analysed to assess coordinate estimation quality. *Results.* Adjusted spatial coordinates and statistical solution characteristics were determined. RMS values did not exceed

24 mm. Phase residuals and baseline checks indicated the adjusted network's internal consistency. The workflow from raw observations to station coordinates and precision estimates was systematised, providing a reference dataset for subsequent inter-epoch comparisons. *Conclusions.* The approach integrates baseline processing, network adjustment, and statistical quality control into a unified workflow, supporting GNSS data preparation for engineering surveying and geodynamic monitoring. The reported metrics characterise solution quality within the observation campaign. Identifying deformation requires repeated observations, verification of reference station stability, and assessment of the statistical significance of inter-epoch displacements accounting for coordinate uncertainty. These estimates can guide the planning of subsequent observation campaigns and the selection of appropriate procedures for coordinate framework quality control.

Keywords: GNSS measurements, static method, geodynamics, geodetic network

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АЛМАТЫНЫҢ ГЕОДИНАМИКАЛЫҚ МОНИТОРИНГІНДЕ СТАТИКАЛЫҚ GNSS-ӨЛШЕМДЕРДІ ӨНДЕУ ТҰЖЫРЫМДАМАСЫ

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Аннотация. *Өзектілігі.* Алматының сейсмикалық белсенді аумағының геодинамикалық мониторингі қайталама геодезиялық бақылаулардың салыстырмалылығын қамтамасыз ететін бірыңғай координаттық негізді талап етеді. Спутниктік өлшеулердің сапасын бақылау ерекше маңызға ие, бұл бақылаулар мен есептеу өңдеудегі қателіктерге байланысты мүмкін болатын деформациялық кенінісулер мен координаттардың өзгеруін ажыратуға мүмкіндік береді. *Мақсаты.* Геодинамикалық мониторинг және геодезиялық желінің ішкі консистенциясын бағалау үшін координаттар жүйесін құру мақсатында GNSS статикалық бақылауларын өңдеудің әдіснамалық негізін қамтамасыз ету. *Материалдар мен әдістер.* Алматының геодезиялық желісінің пункттерінде орындалған GPS, GLONASS және BeiDou мультисистемалық статикалық бақылаулары пайдаланылды. South Geomatics Office бағдарламалық кешеніндегі өңдеу бастапқы деректерді тексеруді, негізгі векторларды есептеуді, фазалық түсініксіздіктерді шешуді және үш өлшемді желіні теңестіруді қамтыды. Белгіленген түсініксіздіктері бар шешімдер алынды. Координаталық анықтамалардың сапасы фазалық ауытқулар, базалық сызықтардың сипаттамалары және RMS көрсеткіштері бойынша бағаланды. Осы сипаттамалардың бірлескен талдауы өңдеу нәтижелерін кешенді бағалауды қамтамасыз етті. *Нәтижелер.* Элементтердің теңдестірілген кеңістіктік координаттары және алынған шешімдердің статистикалық сипаттамалары анықталды. RMS мәндері 24 мм-ден аспады. фазалық бұзылулар мен базалық бақылау нәтижелерін талдау өңделген желінің ішкі консистенциясын көрсетеді. Бастапқы спутниктік бақылаулардан нүктелердің координаттарына және олардың дәлдігін бағалауға көшу реттілігі жүйеленген. Кейінгі кезеңаралық салыстыру үшін бастапқы ақпараттық негіз қалыптастырылды. *Қорытынды.* Қарастырылған тәсіл негізгі сызықтарды өңдеуді, желіні теңестіруді және нәтижелерді статистикалық бақылауды есептеулердің бірыңғай тізбегіне біріктіреді. Оның практикалық маңыздылығы инженерлік-геодезиялық зерттеулер мен геодинамикалық мониторинг үшін GNSS деректерін дайындауды әдістемелік қамтамасыз ету болып табылады. Ұсынылған көрсеткіштер қарастырылған өлшеу циклі шегінде шешімдердің сапасын сипаттайды. Деформацияларды анықтау қайталама бақылауларды, бастапқы нүктелердің тұрақтылығын тексеруді және координаттардың белгісіздігін ескере отырып, кезеңаралық мәншеулердің статистикалық маңыздылығын бағалауды талап етеді. Алынған бағалаулар кейінгі өлшемдерді жоспарлау және координаталық негізді бақылау процедураларын таңдау кезінде қолданылуы мүмкін.

Түйін сөздер: GNSS-өлшеулері, статикалық әдіс, геодинамика, геодезиялық желі

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КОНЦЕПЦИЯ ОБРАБОТКИ СТАТИЧЕСКИХ GNSS-ИЗМЕРЕНИЙ В ГЕОДИНАМИЧЕСКОМ МОНИТОРИНГЕ АЛМАТЫ

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Аннотация. *Актуальность.* Геодинамический мониторинг сейсмоактивной территории Алматы требует формирования единой координатной основы, обеспечивающей сопоставимость результатов повторных геодезических наблюдений. Особое значение приобретает контроль качества спутниковых измерений, позволяющий разграничивать возможные деформационные смещения земной поверхности и изменения координат, обусловленные погрешностями измерений и вычислительной обработки. *Цель.* Разработать методологический подход к обработке статических GNSS-наблюдений для формирования координатной основы геодинамического мониторинга и оценки внутренней согласованности геодезической сети. *Материалы и методы.* В исследовании использованы результаты мультисистемных статических GNSS-наблюдений, выполненных на пунктах геодезической сети Алматы с применением спутниковых систем GPS, GLONASS и BeiDou. Обработка данных осуществлялась в программном комплексе South Geomatics Office и включала проверку исходных наблюдений, вычисление базовых векторов, разрешение фазовых неоднозначностей и уравнивание трехмерной геодезической сети. В результате получены решения с фиксированными фазовыми неоднозначностями. Качество координатных определений оценивалось на основе анализа фазовых невязок, характеристик базовых линий и значений среднеквадратических показателей

(RMS). Совместное рассмотрение указанных параметров позволило выполнить комплексную оценку внутренней согласованности результатов геодезических вычислений. *Результаты.* Определены уравненные пространственные координаты пунктов геодезической сети и рассчитаны статистические характеристики полученных решений. Значения показателя RMS не превышали 24 мм. Анализ фазовых невязок и результатов контроля базовых линий показал внутреннюю согласованность геодезической сети в пределах рассмотренного цикла наблюдений. Систематизирована последовательность обработки спутниковых данных, включающая переход от исходных измерений к определению пространственных координат пунктов и оценке их точности. Сформирована исходная информационная база для последующего сопоставления координат, полученных в разные эпохи наблюдений. *Выводы.* Предложенный методологический подход объединяет вычисление базовых векторов, уравнивание геодезической сети и статистический контроль результатов в единую последовательность обработки статических GNSS-наблюдений. Его практическая значимость заключается в обеспечении методической основы подготовки спутниковых данных для инженерно-геодезических исследований и геодинамического мониторинга. Полученные статистические показатели характеризуют качество координатных решений в пределах одного цикла измерений и не позволяют непосредственно установить наличие геодинамических деформаций. Для выявления и количественной оценки деформационных смещений необходимы повторные наблюдения, проверка стабильности исходных пунктов и определение статистической значимости межэпоховых изменений координат с учетом неопределенности их определения. Результаты исследования могут использоваться при планировании последующих GNSS-наблюдений и совершенствовании процедур контроля координатной основы геодинамического мониторинга Алматы.

Ключевые слова: GNSS-измерения, статический метод, геодинамика, геодезическая сеть

Introduction. Modern Global Navigation Satellite Systems (GNSS) are an effective tool for obtaining high-precision spatial information and are widely used in engineering geodesy, geodynamic studies, and territorial monitoring. The high accuracy of satellite observations makes it possible to form stable geodetic networks designed for long-term observations and analysis of spatial changes in the coordinates of observation points (Konakoglu, 2021; Teunissen et al., 2022; Hofmann-Wellenhof et al., 2021).

An important stage in the organization of satellite observations is the development of a concept for processing static GNSS measurements aimed at ensuring high accuracy and reliability of coordinate determination. Such a concept includes the formation of the geodetic network structure, processing of satellite

observations, analysis of baselines, resolution of phase ambiguities, adjustment of the spatial network, and statistical evaluation of the accuracy of the obtained coordinates (Li et al., 2020; Teunissen et al., 2020).

The Global Navigation Satellite System (GNSS) has become one of the key technologies of modern geodetic positioning, providing high-precision and reliable spatio-temporal information for a wide range of scientific and applied tasks (Montenbruck et al., 2020; Tekenov et al., 2017; Maciuk et al., 2021; Gabsatarov et al., 2022). The principle of GNSS operation is based on a constellation of navigation satellites orbiting the Earth and continuously transmitting radio signals to ground receivers. GNSS receivers record these signals and, through their processing, determine spatial coordinates, velocity, and precise observation time (Li et al., 2023; Nurgaliyeva et al., 2026; Sukhenko et al., 2025; Kashkin et al., 2001).

In the context of monitoring geodynamic processes, static GNSS measurements are of particular importance, as they allow the determination of observation point coordinates with millimeter-level accuracy. Subsequent mathematical processing of such observations makes it possible to detect small horizontal and vertical displacements of the Earth's surface, enabling the analysis of modern deformation processes, the assessment of tectonic activity, and the control of the stability of geodynamically active territories.

Special attention in GNSS data processing is given to the quality control of raw observations, analysis of baseline parameters, and assessment of the accuracy of coordinate solutions. This makes it possible to form a stable and highly accurate geodetic framework for subsequent geodynamic studies. The development and application of a methodologically justified scheme for processing static GNSS measurements is an important prerequisite for ensuring the reliability of monitoring results and increasing the efficiency of using satellite technologies in the territory of the city of Almaty.

Urban areas located in zones of high seismic activity represent complex natural-technogenic systems, the sustainable development of which is impossible without the creation and maintenance of high-precision geodetic networks. The city of Almaty, the largest metropolis and economic center of the Republic of Kazakhstan, is located in one of the most seismically hazardous regions of Central Asia — the foothills of the Northern Tien Shan (Kenjezhan et al., 2022). The complex tectonic structure of the region, the presence of active faults crossing the urban territory, and the history of destructive earthquakes determine the necessity of continuous and detailed monitoring of surface deformation processes and assessment of the geodynamic stability of the urban environment (Figure 1).



Figure 1. Geographical location of the study area.

Geodynamic monitoring in seismically active regions plays a key role in assessing seismic hazards and reducing the risks of natural and technogenic disasters. Modern crustal movements are one of the indicators of the accumulation of elastic stresses in the lithosphere, the release of which may lead to seismic events of varying intensity. For a long time, the basis of geodetic studies of deformations was formed by traditional methods of high-precision leveling and linear-angular measurements. However, the development of Global Navigation Satellite Systems (GNSS) has significantly expanded the possibilities for studying modern crustal movements and has brought geodynamic research to a qualitatively new level (Nurpeisova et al., 2024).

GNSS technologies are currently an integral part of modern geodesy and geophysics. They provide the determination of three-dimensional coordinates of observation points with millimeter-level accuracy within a unified global coordinate system, which is particularly important for analyzing deformations over large spatial and temporal scales. Unlike local geodetic networks, satellite methods make it possible to compare the results of regional observations with global tectonic processes and to analyze the relationship between local deformation fields and the motion of lithospheric plates. The use of static GNSS measurements ensures high accuracy in coordinate determination, stability of solutions, and the possibility of forming long-term coordinate time series, which is especially important for geodynamic monitoring.

The geographical location of Almaty at the junction of the Zailiyskiy Alatau

mountain range and the Ili basin determines the high intensity of modern tectonic movements in the region. The region is characterized by active mountain-building processes accompanied by both vertical and horizontal displacements of the Earth's crust. Historical records indicate a high seismic vulnerability of the territory. The destructive Verny earthquake of 1887, with a magnitude of about M7.3, almost completely destroyed the city of Verny (now Almaty) and caused large-scale landslides and rockfalls in mountainous areas. The Kemin earthquake of 1911, with a magnitude of M8.0—one of the strongest intracontinental earthquakes of the twentieth century—also caused significant damage and led to noticeable residual deformations of the terrain. These events confirm the high tectonic activity of the region and highlight the necessity of continuous monitoring of the geodynamic state of the territory (Figure 2) (Mikhailova et al., 2020).

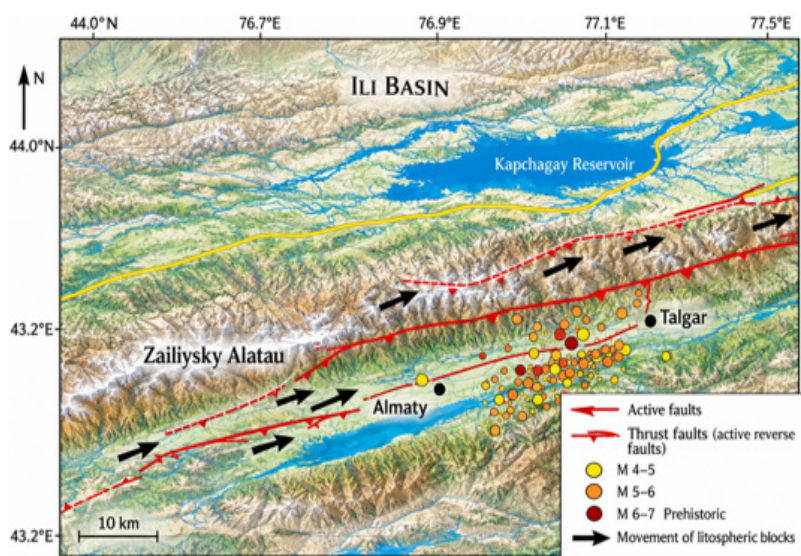


Figure 2. Tectonic and seismic activity of the Almaty region.

The current seismic activity of the region remains high. Every year, hundreds of weak and moderate seismic events are recorded within the Northern Tien Shan, indicating ongoing tectonic processes and the redistribution of stresses within the Earth's crust. Under these conditions, the development of high-precision geodetic monitoring methods capable of detecting even minor surface displacements and identifying trends in deformation processes becomes particularly important. The densification of urban development, expansion of transport infrastructure, construction of high-rise buildings, and increasing population density require obtaining the most accurate information about soil stability, the activity of tectonic faults, and possible surface deformations (Abdrakhmatov et al., 2021).

In this regard, the development of a concept for processing static GNSS

measurements aimed at creating a high-precision geodetic framework for monitoring geodynamic processes in the territory of the city of Almaty is of significant scientific and practical interest. The implementation of this concept involves the analysis of geological and tectonic conditions of the study area and the justification of the configuration of a test GNSS network, conducting a series of static satellite observations using multi-constellation receivers (GPS, GLONASS, BeiDou), and the development and application of a data processing methodology in the South Geomatics Office (SGO) software package to obtain fixed vector solutions. It also includes the rigorous adjustment of the network and statistical evaluation of the accuracy of the obtained coordinates of observation points. Additional attention is given to the analysis of the quality of the obtained solutions and the assessment of their applicability for geodynamic monitoring tasks through comparison of GNSS observation results with existing data on crustal deformation rates and geological and geophysical information of the region (Bürgmann et al., 2013).

The obtained results can be used in the creation and development of long-term geodynamic monitoring systems, as well as in solving engineering and geodetic problems under conditions of seismically active urban territories.

Literature Review. The application of satellite geodetic technologies for studying geodynamics has become a global standard. Numerous studies (Bürgmann, 2013) demonstrate the effectiveness of GNSS networks for monitoring seismic deformations. In tectonically active regions such as the Japanese archipelago, the western coast of the United States (San Andreas Fault), and the Anatolian plate, dense networks of permanent GNSS stations (CORS) operate, providing continuous observation time series (Bürgmann et al., 2013).

For the Central Asian and Tien Shan regions, pioneering work on the use of GPS for geodynamic studies began in the 1990s. Large-scale investigations conducted by Zubovich et al. (2010) made it possible to construct a velocity field of present-day crustal movements for the entire Tien Shan. According to their results, the region experiences intense north–south compression caused by the collision of the Indian and Eurasian plates. Horizontal displacement rates relative to stable Eurasia vary across the region, reaching crustal shortening values of up to 20 mm/year across the entire mountain belt. For the Northern Tien Shan and the Almaty region, displacement rates of about 2–7 mm/year in the northwestern direction relative to the Eurasian plate are typical (Zubovich et al., 2010).

Detailed investigations of active tectonics in the immediate vicinity of Almaty are presented in the works of Grützner et al. (2017). The authors used a combination of paleoseismological data, high-resolution satellite imagery, and digital elevation models to map active faults. In particular, the position of the main frontal fault of the Zailiyskiy Alatau was refined, and previously hidden faults beneath the alluvial deposits of the foothill plain were identified, representing potential seismic hazards for urban infrastructure (Grützner et al., 2017).

In recent years, radar interferometry (InSAR) methods have been significantly

developed, allowing the acquisition of spatial deformation patterns over large areas presented the results of PS-InSAR monitoring of the Almaty territory for the period 2003–2006, identifying local zones of ground subsidence. A more recent study by Bayramov et al. (2024), covering the period 2017–2023, revealed a complex pattern of vertical movements with zones of anomalously high subsidence rates (up to 57 mm/year) and uplift (up to 40 mm/year), correlating with active fault zones and anthropogenic loading. These findings emphasize the necessity of integrating InSAR and high-precision GNSS measurements, where GNSS serves as a reference framework and a means of validating satellite radar data (Bayramov et al., 2024).

The choice of the static GNSS measurement method in this study is due to its highest accuracy and reliability compared with kinematic methods (RTK, PPP). Static observations allow effective averaging of multipath effects and atmospheric delays over longer observation sessions, which is critical for detecting millimeter-scale displacements typical of tectonic processes during the interseismic period. The use of modern processing algorithms implemented in software packages such as South Geomatics Office, Bernese GNSS Software, or GAMIT/GLOBK makes it possible to achieve coordinate determination accuracy at the level of a few millimeters.

Materials and Methods. The spatial configuration of the network is characterized by the presence of baselines of different lengths, which ensures sufficient redundancy of observations and increases the stability of the adjustment results. Such a distribution of stations makes it possible to form short, medium, and long baselines, thereby improving the reliability of coordinate determination (Liu T. et al., 2022).

The formed geometry of the GNSS network ensures the possibility of high-precision determination of three-dimensional coordinates of observation points and meets the requirements for geodetic networks used for monitoring deformation processes in seismically active regions. The presence of baselines of different lengths also increases the resistance of the network to random errors in satellite observations and improves the geometric strength of the solution during network adjustment.

An additional advantage of this configuration is the possibility of quality control through the analysis of geodetic polygon closures and comparison of independent vector solutions. Observation redundancy allows the detection of possible systematic errors and increases the reliability of the obtained coordinate solutions.

Moreover, such a network structure creates favorable conditions for further analysis of spatio-temporal changes in station coordinates, which is an important element of geodynamic monitoring. This makes it possible to detect even minor surface displacements and to use the obtained data to assess modern tectonic movements and deformation processes within the study area.

In general, the selected configuration of the GNSS network provides the

necessary level of accuracy and reliability of measurements, making it an effective tool for solving problems of high-precision geodetic positioning and monitoring geodynamic activity in the Almaty region (Zaitsev et al., 2020).

Within the territory of the city of Almaty, a three-dimensional GNSS network was established, including the following observation stations: ALMA – the reference (fixed) station of the network; CHIL, ESIK, FABR, and KGAI – working GNSS stations.

The ALMA reference station was used as the initial station with fixed coordinates, which ensured a stable geodetic framework during the processing of satellite observations and subsequent network adjustment. The working stations were located in different parts of the study area to ensure an optimal network geometry and the formation of baselines of various lengths.

The network geometry is characterized by the presence of baselines of different lengths, including short, medium, and long baselines. Such a distribution of stations ensures sufficient observation redundancy and increases the stability of the network adjustment results. The presence of redundant baseline connections between stations enables mutual control of measurements, detection of possible gross errors, and improvement of the reliability of the obtained coordinate solutions. The spatial configuration of the GNSS network is shown in Figure 3.

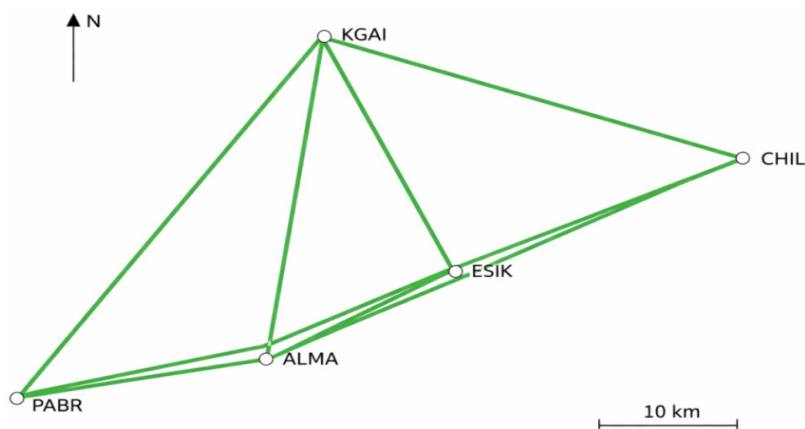


Figure 3. Configuration of the GNSS network in the territory of the city of Almaty, including the reference station ALMA and the working stations CHIL, ESIK, FABR, and KGAI.

The established network configuration provides favorable conditions for conducting high-precision static GNSS measurements and enables reliable determination of the spatial coordinates of stations within a three-dimensional coordinate system. The use of several working stations located at considerable distances from each other increases the geometric stability of the network and reduces the influence of random errors in satellite observations.

In addition, such a GNSS network structure makes it possible to analyze spatio-

temporal variations in station coordinates, which is an important component of geodynamic monitoring. The obtained results can be used to detect modern surface deformation processes, assess tectonic activity, and analyze possible displacements caused by geodynamic and seismic processes.

Thus, the established GNSS network provides the required level of accuracy and reliability of satellite measurements and meets the requirements for geodetic networks used for monitoring geodynamic processes.

Observation Characteristics. GNSS observations were conducted in static mode using multi-frequency receivers. Signals from the GPS, GLONASS, and BeiDou satellite systems were used in the data processing. The duration of each observation session was at least one hour, ensuring reliable ambiguity resolution and high accuracy in baseline solution determination.

Processing of GNSS Observation Data. The processing and adjustment of GNSS observation results were carried out using the specialized software package South Geomatics Office (SGO), designed for the processing of static satellite measurements and the adjustment of geodetic networks. The data processing workflow consisted of several sequential stages aimed at obtaining highly accurate coordinates of the GNSS network stations and evaluating the reliability of the obtained results.

At the first stage, a project was created and the main processing parameters were defined. In the SGO software environment, a new project was established specifying the coordinate system WGS-84 / ITRF2020, the parameters of the reference ellipsoid, and quality control criteria for the obtained solutions. At the same time, threshold values for statistical indicators such as RMS and Ratio, used for evaluating the quality of baseline solutions, were defined.

At the second stage, the raw satellite observation data were imported. RINEX files containing static observations from all stations of the network were loaded into the project. During the import process, the correctness of the file header parameters was verified, including the station name, antenna type and antenna height, as well as the observation time interval. In addition, precise satellite ephemerides (IGS SP3 files) and atmospheric delay models were loaded to improve the accuracy of the computations.

The next stage involved quality control of the raw satellite observations. For this purpose, built-in tools of the SGO software were used to analyze the satellite sky distribution (Skyplot), the signal-to-noise ratio (SNR), and the effects of signal multipath (Multipath). Observations characterized by low signal quality ($\text{SNR} < 25 \text{ dB-Hz}$) were excluded from further processing to improve the accuracy of coordinate solutions.

During the baseline processing stage, vector solutions between GNSS stations were computed using the double-difference phase observation method. The resolution of phase ambiguities was performed in the fixed solution mode (Fixed), indicating reliable integer ambiguity resolution and high accuracy of baseline vectors. To assess the quality of the solutions, the following criteria were applied:

Ratio ≥ 3 and RMS < 30 mm. If unsatisfactory results were obtained, additional parameter adjustments and observation editing were performed.

After the computation of baseline vectors, an analysis of geodetic polygon closures was carried out. This procedure allows the control of linear misclosures and the detection of possible systematic errors in the observations. The verification of network closures is an important stage of geodetic network quality control and confirms the consistency of the obtained baseline solutions. The overall algorithm for GNSS data processing implemented in this study is shown in Figure 4.

Subsequently, a rigorous adjustment of the GNSS network was performed using the least squares method in three-dimensional space. As a result of the adjustment, the most probable coordinates of all network stations were determined. The obtained coordinates were initially computed in the spatial Cartesian coordinate system (X, Y, Z), after which they were transformed into the geographic coordinate system, including latitude (B), longitude (L), and ellipsoidal height (H).

The final stage of processing involved a statistical evaluation of the accuracy of the obtained results. The SGO software generated reports containing the root mean square errors (RMS) of station coordinates, covariance matrices, error ellipses, and the a posteriori variance of unit weight. The performed statistical analysis confirmed that the accuracy of the observations is consistent with the obtained coordinate solutions.

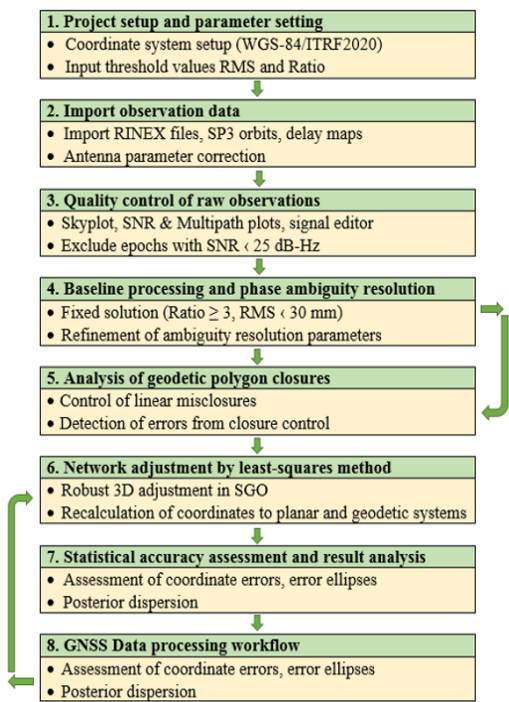


Figure 4. Workflow of static GNSS observation processing in the South Geomatics Office (SGO) software package.

Results. The results of the three-dimensional adjustment of the GNSS network in the Cartesian coordinate system are presented in Table 1. The table provides the spatial coordinates of the network stations in the X, Y, Z system, as well as statistical indicators of coordinate determination accuracy, including the root mean square error (RMS) of the solution and the standard deviations for each coordinate component (σX , σY , σZ).

The ALMA station was used as the reference (fixed) point of the network, and its coordinates were assumed to remain unchanged during the adjustment process; therefore, the values of RMS and standard deviations for this station are equal to zero. The coordinates of the remaining stations of the network – CHIL, ESIK, FABR, and KGAI – were determined as a result of the adjustment of GNSS observations.

The obtained values of the root mean square error for the working stations of the network range from 0.016 to 0.022 m, indicating a high accuracy of spatial coordinate determination. The lowest RMS value is observed for station FABR (0.016 m), while for stations CHIL and ESIK the RMS value is 0.022 m, and for station KGAI it is 0.021 m.

Table 1. Results of the three-dimensional adjustment of the GNSS network (Cartesian coordinates XYZ).

Station	X (m)	Y (m)	Z (m)	RMS (m)	σX (m)	σY (m)	σZ (m)
ALMA	1 052 765.268	4 533 187.935	4 348 007.129	0.000	0.000	0.000	0.000
CHIL	941 381.753	4 532 011.129	4 374 235.988	0.022	0.008	0.008	0.016
ESIK	1 016 628.714	4 531 019.808	4 358 735.668	0.022	0.008	0.008	0.015
FABR	1 095 957.373	4 528 248.243	4 342 694.945	0.016	0.006	0.006	0.011
KGAI	1 031 402.306	4 489 757.727	4 397 096.438	0.021	0.007	0.007	0.015

The analysis of coordinate standard deviations shows that the accuracy of the horizontal coordinates (σX and σY) averages 0.006–0.008 m, while the vertical coordinate component (σZ) is slightly higher, ranging from 0.011 to 0.016 m, which is typical for static GNSS processing results. The higher uncertainty in the vertical component is due to the geometry of the satellite constellation and the greater sensitivity of height determinations to atmospheric influences.

Overall, the obtained accuracy values indicate the high reliability of the GNSS network adjustment results. The achieved level of accuracy meets the requirements for geodetic networks used in high-precision positioning and geodynamic monitoring tasks, confirming the suitability of the established GNSS network for conducting geodynamic studies in the city of Almaty.

The results of the three-dimensional adjustment of the GNSS network in the geographic coordinate system are presented in Table 2. The table provides the corrected geographic coordinates of the network stations – latitude (B), longitude (L), and ellipsoidal height (H), as well as the root mean square error of coordinate determination (RMS) (Turekhanova et al., 2022).

Table 2. Results of the three-dimensional adjustment of the GNSS network (geographic coordinates BLH).

Station	Latitude (N)	Longitude (E)	Ellipsoidal height H (m)	RMS (m)
ALMA	43°14'46.44115"	76°55'32.40607"	786.816	0.000
CHIL	43°34'22.14476"	78°15'55.75283"	593.753	0.024
ESIK	43°22'45.10366"	77°21'14.15669"	756.058	0.023
FABR	43°10'46.54652"	76°23'40.25605"	909.640	0.017
KGAI	43°51'31.09092"	77°03'44.24196"	457.466	0.023

The obtained RMS values for the working stations range from 0.017 to 0.024 m, indicating a high accuracy of geographic coordinate determination. The smallest root mean square error is observed at station FABR (0.017 m), while for stations CHIL and KGAI the RMS values are 0.024 m and 0.023 m, respectively. For station ESIK, the RMS value is 0.023 m, which also corresponds to the level of accuracy typical for static GNSS measurements.

The analysis of ellipsoidal heights shows a significant range of elevation values among the network stations, reflecting the topographic features of the study area. The maximum ellipsoidal height is observed at station FABR (909.640 m), located in the mountainous part of the region, whereas the minimum height is recorded at station KGAI (457.466 m), situated in relatively lower terrain areas. The stations ALMA, CHIL, and ESIK occupy intermediate elevations.

To analyze the spatial distribution of accuracy in the studied GNSS network, the baseline distances between the reference and target stations were compared against the formal uncertainty estimates of their coordinates. Such an analysis makes it possible to evaluate the heterogeneity of the obtained solutions and define the constraints for their use in further comparisons of observational data. The value of... was used as a generalized metric of formal spatial accuracy

$$m_3D_i = \sqrt{\sigma_{X_i}^2 + \sigma_{Y_i}^2 + \sigma_{Z_i}^2} = \sqrt{t_r c_i} \quad (1)$$

where $\sigma_{X_i}^2, \sigma_{Y_i}^2, \sigma_{Z_i}^2$ - are the standard deviations of the station's geocentric coordinates;

$t_r c_i$ - the covariance matrix of its coordinates.

This measure characterizes the total variance of a point's spatial position within the adopted adjustment model.

The spatial distance to the reference station is calculated using the formula

$$L_i = \sqrt{(X_i - X_{ALMA})^2 + (Y_i - Y_{ALMA})^2 + (Z_i - Z_{ALMA})^2} \quad (2)$$

where L_i - is the spatial distance from the station being determined to ALMA;

X_i, Y_i, Z_i - are the geocentric coordinates of the station being determined;

$X_{ALMA}, Y_{ALMA}, Z_{ALMA}$)-are the geocentric coordinates of the ALMA reference station.

The calculated values were obtained using the coordinates and standard deviations presented in Table 3.

Table 3. Calculated values obtained from coordinates and standard deviations.

Point	Spatial distance to ALMA, km	Formal dimension (m_3D), mm
CHIL	114,436	19,6
ESIK	37,758	18,8
FABR	43,797	13,9
KGAI	68,937	18,0

Within the network under consideration, the values of (m_3D) range from 13.9 to 19.6 mm. The smallest formal uncertainty in spatial position was found at the FABR station, and the largest at CHIL. However, for the four stations studied, no monotonic increase in uncertainty was observed as the distance to ALMA increased.

The estimates obtained are relative to the fixed ALMA coordinates. The zero standard deviations for the reference station are due to the adopted constraints in the adjustment and do not confirm its physical immobility. The stability of the reference point must be verified using repeat observations and external reference data.

To interpret horizontal and vertical displacements, it is necessary to transform from geocentric coordinates to the local East–North–Up system with the corresponding transformation of the covariance matrix. The detection of deformations should be based on a comparison of inter-epoch changes in coordinates with the uncertainty of these changes.

The presented analysis characterizes the formal accuracy of the initial coordinate frame and determines the directions for its subsequent experimental verification.

The estimate used (m_3D) refers to standard measures of formal accuracy; in this article, it is presented as a supplementary analysis of our results, without claiming to develop a new mathematical model. The difference between formal and experimentally verified accuracy is discussed in ESA publications.

Based on the data in Table 3, $m_{3D} = \sqrt{384} = 19.6$ mm.

Overall, the obtained coordinate solutions are characterized by high accuracy and consistency, confirming the correctness of the performed GNSS observation processing and the stability of the network adjustment. The achieved level of accuracy allows the established network to be used for high-precision positioning and geodynamic monitoring tasks.

Discussion. The obtained results of GNSS observation processing indicate a high internal consistency and stability of the established three-dimensional GNSS network located within the territory of the city of Almaty. All vector solutions of the baselines were obtained with fixed phase ambiguities, which is an important

indicator of the correct resolution of integer phase ambiguities and the high accuracy of satellite data processing. This also indicates favorable observation conditions, sufficient geometry of the satellite constellation, and the correctness of the applied mathematical model for data processing.

The analysis of phase residuals is one of the key criteria for assessing the quality of GNSS data processing. The conducted study showed that the residuals of phase measurements for individual satellites exhibit a random distribution pattern with mean values close to zero. The absence of pronounced trends, abrupt jumps, or systematic shifts indicates the correct compensation of the main sources of errors, including atmospheric delays, orbital errors, and receiver hardware inaccuracies.

The considered example of the distribution of phase residuals for satellite G02 demonstrates the stability of phase observations throughout the entire observation session. The residuals are presented as a function of time by observation epochs, which makes it possible to assess the dynamics of phase measurements and the correctness of phase ambiguity fixing. The minimum residual value is -0.069 m, the maximum is 0.091 m, with a mean value of -0.009 m and a standard deviation of 0.028 m. The mean value close to zero indicates the absence of systematic bias in phase measurements and confirms the adequacy of the applied data processing model.

The distribution of residuals has a quasi-random character and does not show breaks in the time series, which indicates the absence of cycle slips during the entire observation period. A slight smooth trend observed at the initial segment of the time series may be associated with the stabilization of the solution during the initial phase of processing and does not have a significant impact on the final accuracy of the computed baseline vectors.

The amplitude of phase residual variations remains within ± 0.1 m, which is typical for high-quality static GNSS processing. Such a range of values confirms the stability of phase observations and the sufficient geometry of the satellite constellation during the measurement period. It also indicates a minimal influence of multipath effects and atmospheric disturbances on the processing results.

An additional indicator of GNSS processing quality is the accuracy of determining the coordinates of the network stations. The obtained values of the root mean square error (RMS) do not exceed 0.024 m, which meets the requirements for high-precision geodetic networks used in engineering geodesy and geodynamic monitoring. The achieved level of accuracy confirms the correctness of satellite observation processing and the stability of the network adjustment procedure performed using the least squares method.

The geometry of the established GNSS network also plays an important role in ensuring high accuracy of the results. The presence of baselines of different lengths and observation redundancy ensures the network's resistance to local errors and improves the reliability of station coordinate determination. Such a network configuration makes it possible to control the closure of geodetic polygons and provides the ability to detect possible anomalies in the observation results.

Conclusions. During the study, a three-dimensional GNSS network was established, including the reference station ALMA and the working stations CHIL, ESIK, FABR, and KGAI, located within the territory of the city of Almaty and its surrounding areas. The spatial configuration of the network provides baselines of different lengths and sufficient observation redundancy, which increases the stability of the adjustment and the reliability of the obtained coordinate solutions.

The results of the GNSS network adjustment showed that the root mean square errors of the station coordinates do not exceed 0.024 m, which meets the requirements for high-precision geodetic networks. The analysis of phase residuals also confirmed the stability of phase measurements and the absence of cycle slips during the entire observation period. The residual distribution has a random character, and their amplitude does not exceed ± 0.1 m, which is typical for high-quality static GNSS processing.

The obtained accuracy indicators confirm the high reliability of the established geodetic network and the possibility of its use for high-precision positioning tasks. The formed GNSS network provides the required level of accuracy for detecting spatio-temporal variations in station coordinates and makes it possible to identify small deformations of the Earth's surface.

The results of the study demonstrate the effectiveness of using static GNSS measurements for the formation of high-precision three-dimensional geodetic networks in seismically active urban territories. The use of such networks creates a reliable basis for monitoring modern geodynamic processes and can serve as an important tool for geodynamic studies in the city of Almaty.

Further development of this GNSS network and the implementation of repeated observation cycles will allow the analysis of spatio-temporal dynamics of station coordinates, which is of great importance for improving the efficiency of geodynamic monitoring systems in the region.

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