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CONCEPTUAL MODELING OF A GNSS-BASED GEODETIC CONTROL NETWORK FOR ELEVATED METRO CONSTRUCTION (CASE STUDY: TASHKENT CITY)

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Abstract. This study presents a conceptual modeling of a GNSS-based geodetic control network for elevated metro construction using open spatial data. A 12 km model metro corridor in Tashkent city was analyzed using SRTM digital elevation data and OpenStreetMap infrastructure layers to simulate the route alignment. Theoretical accuracy assessments of GNSS Static and Real-Time Kinematic (RTK) methods were conducted and compared against conventional polygonometric surveying. Results demonstrate that GNSS Static post-processing provides horizontal accuracy of ±5 mm and vertical accuracy of ±8 mm, making it the most suitable method for rail alignment control. RTK mode offers efficient real-time accuracy for construction monitoring. An optimal control point spacing of 2 km is recommended for this type of infrastructure, with reduced intervals to 1 km in sections with terrain gradients exceeding 3%.

Keywords: elevated metro, GNSS, RTK, geodetic control network, conceptual modeling, accuracy assessment, Tashkent.

Annotatsiya. Mazkur tadqiqotda yer usti metrosi qurilishi uchun ochiq fazoviy ma’lumotlar asosida GNSS texnologiyalariga tayangan geodezik tayanch tarmoqning konseptual modellashtirish masalalari yoritilgan. Tadqiqot obyekti sifatida Toshkent shahri hududida joylashgan 12 km uzunlikdagi model metro yo‘lagi tahlil qilindi. Trassa yo‘nalishini modellashtirish maqsadida SRTM raqamli relyef ma’lumotlari hamda OpenStreetMap infratuzilma qatlamlaridan foydalanildi. GNSS Static va Real-Time Kinematic (RTK) usullarining nazariy aniqlik ko‘rsatkichlari baholanib, ularning an’anaviy poligonometriya usuli bilan qiyosiy tahlili amalga oshirildi. Tadqiqot natijalari GNSS Static postprotsessing rejimi gorizontal ±5 mm va vertikal ±8 mm aniqlikni ta’minlashini hamda rel’s yo‘li o‘qini belgilash uchun eng maqbul usul ekanligini ko‘rsatdi. RTK rejimi esa qurilish jarayonida tezkor monitoring ishlarini amalga oshirishda samarali ekani aniqlandi. Mazkur turdagi infratuzilma obyektlari uchun tayanch punktlarni 2 km oraliqda joylashtirish optimal deb tavsiya etiladi, relyef qiyaligi 3% dan ortiq bo‘lgan uchastkalarda esa intervalni 1 km gacha qisqartirish maqsadga muvofiq hisoblanadi.

Kalit so‘zlar: yer usti metrosi, GNSS, RTK, geodezik tayanch tarmoq, konseptual modellashtirish, aniqlik baholash, Toshkent shahri.

Аннотация. В данном исследовании представлена концептуальная модель геодезической сети управления на основе GNSS для строительства надземного метрополитена с использованием открытых пространственных данных. Для моделирования трассы был проанализирован 12-километровый модельный коридор метрополитена в городе Ташкенте с использованием цифровых данных о рельефе SRTM и слоев инфраструктуры OpenStreetMap. Были проведены теоретические оценки точности методов GNSS Static и Real-Time Kinematic (RTK) и проведено сравнение с традиционной полигонометрической съемкой. Результаты показывают, что постобработка GNSS Static обеспечивает горизонтальную точность ±5 мм и вертикальную точность ±8 мм, что делает его наиболее подходящим методом для контроля трассы рельсов. Режим RTK обеспечивает эффективную точность в реальном времени для мониторинга строительства. Для данного типа инфраструктуры рекомендуется оптимальное расстояние между контрольными точками в 2 км, с уменьшением интервала до 1 км на участках с уклоном местности более 3%.

Ключевые слова: надземное метро, GNSS, RTK, геодезическая сеть управления, концептуальная модель, оценка точности, Ташкент.

INTRODUCTION

The modernization of urban transport infrastructure has led to increasing interest in elevated metro systems, which offer advantages in terms of land use efficiency and construction cost compared to underground solutions. Elevated metro lines, supported by viaduct structures, impose strict requirements on geodetic control: rail surface planimetric accuracy of ±10 mm and vertical accuracy of ±5–10 mm must be maintained throughout the construction and operational lifecycle [1]. Classical geodetic methods—polygonometry and triangulation—have historically provided the required accuracy for alignment control. However, these methods are time-consuming, require intervisibility between stations, and are sensitive to atmospheric refraction in urban environments [2]. The emergence of Global Navigation Satellite Systems (GNSS) has fundamentally transformed geodetic surveying practice by enabling precise positioning without line-of-sight constraints [3].

GNSS-based control networks, using both Static and Real-Time Kinematic (RTK) modes, have been successfully applied in metro and railway construction in numerous countries. Static GNSS post-processing with baselines processed in network adjustment routinely achieves sub-centimetre accuracy, fulfilling the requirements for primary geodetic control [4]. RTK mode, while slightly less precise, offers significant advantages for construction monitoring due to its real-time output and minimal setup time [5]. Despite the maturity of GNSS technology, its systematic application to the design of geodetic control networks for elevated metro projects in Central Asia remains underexplored. This study addresses this gap by presenting a conceptual GNSS network design for a 12 km model elevated metro corridor in Tashkent, Uzbekistan, based on open spatial data (OpenStreetMap, SRTM). The study evaluates the theoretical accuracy of GNSS Static and RTK modes, compares them with polygonometric methods, and recommends optimal control point configurations.

STUDY AREA AND DATA SOURCES

The city of Tashkent, the capital of Uzbekistan, was selected as the study area due to its active urban development and ongoing transport infrastructure investment. A model metro corridor of 12 km length was delineated based on a representative urban route scenario.

The following open spatial datasets were used in the study:

- OpenStreetMap (OSM): road and urban infrastructure layers for route alignment context.
- Shuttle Radar Topography Mission (SRTM) digital elevation model at 30 m spatial resolution: used to extract the longitudinal elevation profile of the corridor.
- Published GNSS technical specifications and instrument datasheets for theoretical accuracy computation.

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The SRTM-derived elevation profile enabled identification of terrain gradient zones along the corridor, which informed the recommended control point spacing (Section IV).

METHODOLOGY

GNSS Control Network Configuration

A network design was adopted in which GNSS control points are placed at approximately 2 km intervals along the metro route, yielding a total of seven primary control points for the 12 km corridor. The network consists of:

- Two reference (base) stations (R1, R2) installed at the termini of the corridor, tied to the national geodetic datum.
- Five intermediate control points (P1–P5) evenly distributed along the alignment.

The seven points form a closed geodetic network, enabling internal consistency checks and rigorous network adjustment. Figure 1 illustrates the schematic layout of the control network along the modelled metro corridor.

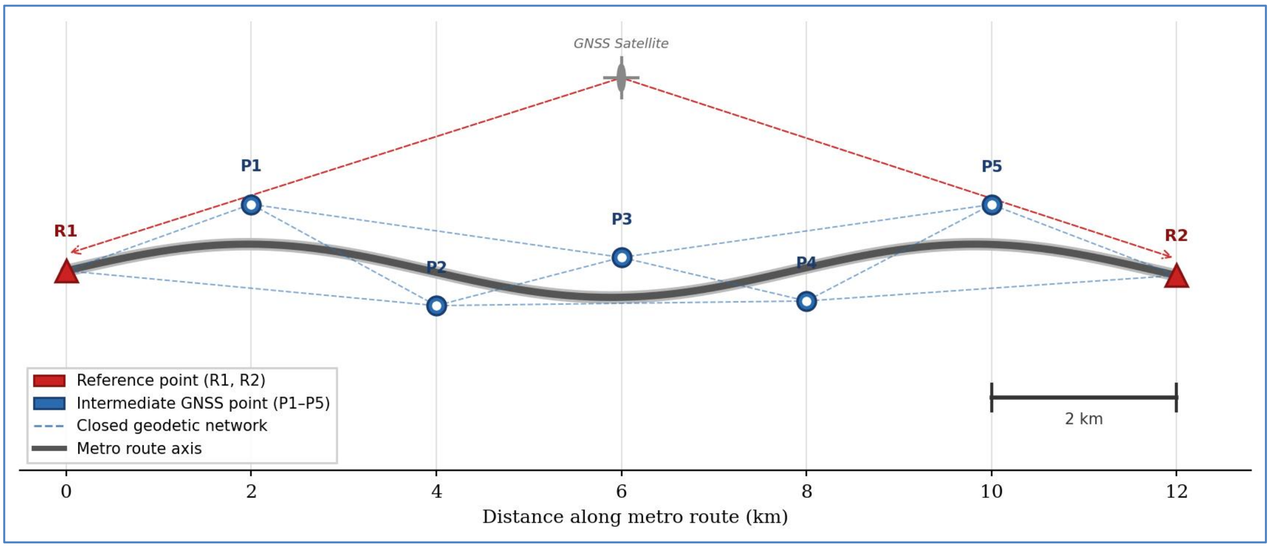

Figure 1. Schematic layout of GNSS control points along the 12 km model elevated metro route. Two reference stations (R1, R2) are positioned at route termini; five intermediate points (P1–P5) are deployed at 2 km intervals. The closed geodetic network geometry enables redundant accuracy control.

Theoretical Accuracy Assessment

The positioning accuracy of GNSS measurements is commonly expressed using the Root Mean Square Error (RMSE) model:

$$RMSE = \sqrt{\frac{\sum (x_i - x_{true})^2}{n}}$$

where σ_0 is the base precision and k is the distance-dependent coefficient (ppm).

For GNSS RTK mode, the manufacturer-specified accuracy values are:

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- Horizontal accuracy: ±(8 mm + 1 ppm)
- Vertical accuracy: ±(15 mm + 1 ppm)

For GNSS Static post-processing mode:

- Horizontal accuracy: ±(3–5 mm)
- Vertical accuracy: ±(5–8 mm)

For a baseline length of 12 km, the distance-dependent component (1 ppm) contributes 12 mm. The resulting maximum expected uncertainty for RTK mode is therefore approximately ±20 mm, while Static mode yields 8–10 mm. These values were used as the basis for method comparison.

Comparison with Conventional Methods

A structured comparison of positioning accuracy was conducted between polygonometric traversing, GNSS RTK, and GNSS Static methods. Table 1 summarises the theoretical accuracy parameters for each method.

Table 1. Comparison of geodetic survey methods for metro route control.

Method	Horizontal Accuracy (mm)	Vertical Accuracy (mm)	Main Advantage
Polygonometry	±20–30	±15–20	Low equipment cost
GNSS RTK	±10–20	±15	Fast acquisition
GNSS Static	±5	±8	Highest accuracy

The accuracy comparison is further illustrated in Figure 2, which shows horizontal and vertical accuracy values in millimetres for each surveying method. GNSS Static post-processing clearly achieves the best positional accuracy and is therefore recommended as the primary method for establishing the geodetic control network.

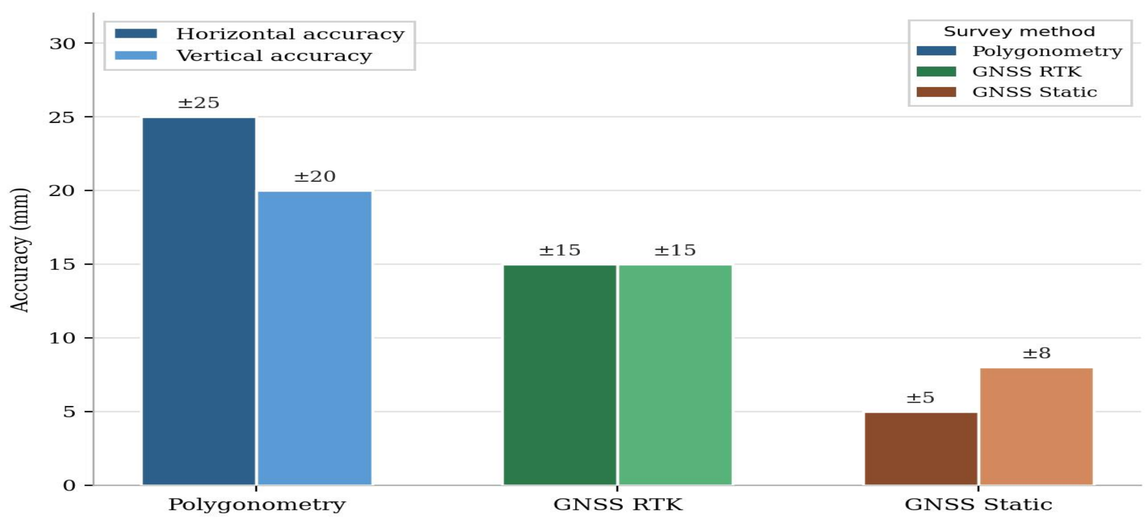

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Figure 2. Comparison of positional accuracy for three geodetic survey methods: polygonometry, GNSS RTK, and GNSS Static post-processing. Values represent theoretical accuracy in millimetres for horizontal and vertical components. Error bars indicate the range of published specifications.

OPTIMAL CONTROL POINT DISTRIBUTION

Analysis of the SRTM-derived longitudinal profile revealed gradient variations along the modelled corridor. Sections with terrain gradient exceeding 3% require denser control to maintain alignment accuracy and enable early detection of differential settlement.

Based on the accuracy analysis and terrain assessment, the following spacing guidelines are recommended:

- Flat terrain (gradient < 3%): control point interval of 2 km.
- Sections with gradient > 3%: reduced interval of 1 km.

The proposed control point density ensures that construction deformation can be detected before it accumulates beyond the design tolerance. Early detection is particularly critical for viaduct-supported elevated metro structures, where differential settlement of foundations can cause rail misalignment [6].

The two-reference-station configuration (R1, R2) at the route termini anchors the network to the national coordinate system, while the intermediate points (P1–P5) provide densification for construction control. This geometry also permits closed-loop network adjustment, enabling statistical outlier detection and quality assurance of the measured baselines [7].

RESULTS

The conceptual modeling study yielded the following principal findings:

- A network of 7 to 10 GNSS control points is sufficient for a 12 km elevated metro corridor, subject to terrain gradient conditions.
- GNSS Static post-processing provides the highest positional accuracy (±5 mm horizontal, ±8 mm vertical) and is recommended as the primary method for establishing the geodetic reference network.
- GNSS RTK mode is suitable for real-time construction monitoring, offering a practical trade-off between speed and accuracy.
- Open spatial data (OpenStreetMap, SRTM) proved adequate for conceptual network design and preliminary accuracy simulation in the absence of field measurements.
- Closed geodetic network geometry, with two reference stations and five intermediate points, enables rigorous internal accuracy control and network adjustment.

DISCUSSION

Compared to conventional polygonometric traversing, GNSS-based geodetic networks offer superior accuracy, reduced setup time, and seamless integration with national and global reference frames. The ability to process baselines in a rigorous network adjustment, rather than sequentially, is a key advantage for metro-scale control networks where accumulated errors must be rigorously controlled [8].

The use of open spatial data for preliminary network design represents a cost-effective approach for the early design stage. While SRTM elevation data (30 m resolution) is not suitable for construction-grade surveys, it is adequate for identifying gradient zones that inform control point spacing decisions at the conceptual stage [9].

A limitation of the present study is that it relies on theoretical accuracy figures rather than field-measured baselines. Future work should validate the proposed network design through practical GNSS observations and formal network adjustment using least-squares estimation. Additionally, the effect of multipath interference in urban and viaduct environments—a known challenge for GNSS in dense urban settings—should be assessed for the specific Tashkent corridor [10].

CONCLUSION

This study demonstrated the feasibility of designing a GNSS-based geodetic control network for elevated metro construction using open spatial data. A conceptual network was designed for a 12 km model corridor in Tashkent, comprising two reference stations and five intermediate control points at 2 km intervals. Theoretical accuracy assessment confirmed that GNSS Static post-processing meets the ±5–10 mm accuracy requirements for rail alignment control, outperforming both GNSS RTK and classical polygonometry.

The key recommendations arising from the study are:

- Adopt GNSS Static post-processing as the primary method for establishing the geodetic control network for elevated metro construction.
- Use GNSS RTK for real-time construction monitoring and setting-out operations.
- Deploy control points at 2 km intervals in flat terrain and at 1 km intervals where terrain gradient exceeds 3%.
- Anchor the network at both route termini with reference stations tied to the national geodetic datum.

The results of this study can be directly applied to the planning of geodetic control for metro infrastructure projects in Uzbekistan and comparable urban environments in the region.

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