

ORIGINAL ARTICLE

Analysis of the potential of low-cost GNSS receivers in the establishment of geodetic control networks using a static technique

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Abstract

Recent developments in Global Navigation Satellite System (GNSS) technology have significantly improved the performance and quality of inexpensive measuring equipment, namely low-cost GNSS. These devices enable positioning with an accuracy comparable to that of geodetic-grade GNSS receivers. The main objective of this study was to verify whether such receivers are sufficient for establishing geodetic control networks using static measurement techniques, which require high accuracy in both horizontal and vertical directions. Field tests were carried out using several low-cost GNSS receivers and antennas, operated simultaneously with geodetic-grade instruments. The collected observations were processed using commercial software and compared with a benchmark campaign. The analyses considered the lengths of measurement sessions, information about antenna reference point offsets used, and the challenges in calculating baselines with low-cost GNSS receivers. Special attention was paid to minimizing the time required for measurement activities, while maintaining the required accuracy parameters. The results show that low-cost GNSS receivers fulfill the requirements of the relevant national guidelines – i.e., achieving vertical positioning accuracy of not exceeding 0.01 m, as well as horizontal positioning errors of well below 0.07 m. The conducted analyses further confirmed the stability and repeatability of the obtained results for sessions lasting 20 minutes or longer. The conducted work and obtained results confirm that low-cost GNSS receivers' affordability combined with their high precision makes them a valuable alternative to geodetic instruments in many practical applications.

Keywords: low-cost GNSS receiver, geodetic control networks, GNSS static technique

1 Introduction

Global Navigation Satellite Systems (GNSS) play a crucial role in various sectors of everyday life. With ongoing technological development, these systems have become widely applied in areas such as road transport (Jagelčák et al., 2024), as well as in other civil fields including telecommunications and the military sector (Wu et al., 2018). To reduce operational costs, low-cost surveying equipment is increasingly used in various geodetic applications, offering high accuracy and positioning quality. This may constitute an alternative to high-precision instruments, which are characterized by higher costs associated with their use (Hamza et al., 2023).

Measurements using satellite navigation systems require the use of devices, such as GNSS receivers and antennas, capable of recording and appropriately processing signals transmitted by satellites belonging to different GNSS constellations. Due to rapid technological progress, their design and technical parameters are con-

tinuously improved to enhance performance combined with equipment miniaturization and lower production costs. These devices can be classified into various groups on the basis of their operational characteristics and technical specifications. GNSS surveying with the accuracy required for the establishment of geodetic control networks can be performed using two types of devices. The first group comprises high-precision geodetic receivers manufactured by world-leading companies. The second group consists of low-cost instruments, which are gaining increasing popularity (Fei et al., 2024; Hamza et al., 2021). A separate category is represented by receivers used on everyday devices, such as mobile phones, smartwatches, and car navigation systems.

Currently, satellite navigation systems are of fundamental importance in land surveying, starting from their fundamental role in establishing reference frames (i.e., establishment of geodetic control networks) to topographic surveys. The use of geodetic GNSS receivers is commonly associated with tasks performed by survey-

ors to determine the position of points on the Earth's surface. With the evolution of modern technologies and growing knowledge concerning GNSS systems, these devices are now applied not only to determine the object location in the field but also in various scientific studies and research projects. High-precision GNSS receivers are characterized by significant costs, which may constitute a limitation in their usage in certain sectors. Continuous technological innovations have led to the increasing adoption of an alternative to high-end instruments, called low-cost GNSS receivers. Although low-cost GNSS receivers are considerably cheaper, when an appropriate measurement configuration is applied they are capable of delivering results comparable in accuracy to those obtained from geodetic-grade receivers (Krietemeyer et al., 2020). The research findings highlight the considerable potential of low-cost GNSS receivers and antennas in applications related to displacement detection (Hamza et al., 2021), but also other scientific applications – GNSS reflectometry (Aichinger-Rosenberger et al., 2023) or intelligent devices (Fei et al., 2024). Additionally, these receivers are increasingly recognized for their ability to deliver high-precision observations suitable for advanced positioning and tropospheric parameter estimation (Marut et al., 2022). Low-cost GNSS receivers with properly calibrated low-cost antennas can achieve a displacement measurement accuracy around 4 mm horizontally and 6 mm vertically. Although compared to high-precision GNSS receivers, low-cost GNSS receivers produce noisier data, millimeter-level accuracy is still attainable (Hamza et al., 2021). Low-cost U-blox ZED-F9P receivers can deliver highly accurate tropospheric delay estimates, but antenna quality remains a limiting factor (Krietemeyer et al., 2020). Appropriate antenna selection has a significant impact on data quality because some cheap antennas achieve accuracy comparable to professional devices, whereas others are characterized by low signal acquisition ratios, particularly for the second frequency of GPS and GLONASS (Marut et al., 2024).

Advances in scientific methods measurement instrumentation have significantly increased the positioning performance achievable with low-cost surveying equipment. Experimental results show that by employing low-cost GNSS receivers together with relative positioning in the static mode, it is possible to achieve measurement accuracies at the centimeter level, with solution quality decreasing on longer baselines (Wielgocka et al., 2021). Furthermore, for baselines exceeding 25 km, difficulties with ambiguity resolution have been observed, which represents a significant limitation in the use of low-cost GNSS receivers for geodetic applications (Kazmierski et al., 2023). To avoid baseline length issues when measuring with low-cost GNSS receivers, the study suggested including several high-precision geodetic-grade GNSS receivers only for connecting the local measurements with reference networks of Continuously Operating Reference Station (CORS), often located tens of kilometers away. In this strategy, low-cost GNSS receivers densify the geodetic network, but high-precision ones remain essential for linking measurements to distant reference stations (Kazmierski et al., 2023). Tests conducted using both geodetic-grade and low-cost GNSS receivers have shown that geodetic-grade instruments exhibit better performance compared with low-cost devices, primarily due to fewer cycle slips and lower phase observation noise (Hamza et al., 2021). Although these differences are not substantial, they may still lead to difficulties in high-precision GNSS measurements carried out with low-cost GNSS receivers. Additionally, proper sampling frequency in low-cost GNSS setups is crucial, as improper sampling can reduce measurement precision and may cause data loss (Romero-Andrade et al., 2021). In view of all the factors discussed above, it is essential to be aware of the limitations associated with the use of low-cost GNSS equipment when planning measurements. Understanding these limitations enables the development of a measurement strategy that ensures the intended results can be achieved.

The main objective of this study is to assess the potential of low-cost GNSS receivers for establishing geodetic control networks

using a static technique. According to the literature, static measurements with low-cost GNSS receivers can achieve one-centimeter-level positioning accuracy under optimal surveying and processing strategy, which aligns with the legal requirements in Poland for detailed geodetic control networks. Therefore, the target accuracy in this study was defined in accordance with the provisions of the effective regulation and set to 0.07 m for horizontal coordinates and 0.01 m for vertical coordinates (Regulation, 2021). The accuracy of coordinate determination was assessed based on the differences between the results of two independent measurements carried out using both high-precision and low-cost GNSS receivers (Regulation, 2021). The calculations are referenced to higher-order geodetic control network – horizontally to ASG-EUPOS network stations, which constitute the fundamental CORS network in Poland, and vertically – to selected points of the vertical control network surrounding the area. The obtained results were expressed in the official national spatial reference systems – horizontal coordinates in the PL-2000 coordinate system based on the PL-ETRF2000 reference frame, and vertical coordinates in the PL-EVRF2007-NH vertical reference frame. The following study also examines the impact of calibrating low-cost GNSS antennas on the obtained results and determines minimum observation session length required to meet the specified horizontal and vertical positional accuracy threshold. Additionally, the research addresses how to overcome the hardware-related limitations of low-cost GNSS sensors – such as baseline processing constraints and antenna phase center (ARP/PCO) offsets while maintaining measurement stability and repeatability. Furthermore, the study answers the question of what measurement duration using low-cost receivers is sufficient to achieve the expected results. These findings will help reduce the costs of conducting field measurement campaigns as well as the acquisition of survey equipment, which can effectively replace expensive geodetic-grade instruments.

2 Methods

This section outlines the measurement tools, methods and computational techniques employed in this study. It focuses particularly on low-cost GNSS receivers and their application in precision geodetic measurements.

2.1 Set up and methodology

The fieldwork involved establishing a geodetic control network using GNSS static surveying during two independent campaigns, each containing two measurement sessions. The first benchmark campaign was carried out using high-precision geodetic receivers, providing reference data for the analysis of measurements conducted during the second campaign performed with low-cost GNSS receivers.

To ensure proper height referencing, geometric levelling was carried out from four wall benchmarks to the measurement points. During both measurement campaigns, GNSS antennas were positioned using an identical procedure. They were mounted on surveying poles stabilized with tripods to precisely place the antenna above each point at a consistent height. All GNSS receivers were set to a 1-second observation recording interval, to facilitate the reduction of the observation session length, which was a key aspect investigated in this study.

Next, observations from both campaigns were post-processed in separate processes. Firstly, data from the first campaign were processed. The processing of experimental data was conducted in several scenarios, considering different lengths of measurement sessions (Figure 1). Specifically, the continuous dataset recorded during the four-hour field campaign was divided into shorter, independent observation sessions of 120, 60, 30, 25, 20, and 15 minutes, which served as designated campaign design scenarios. Each sce-

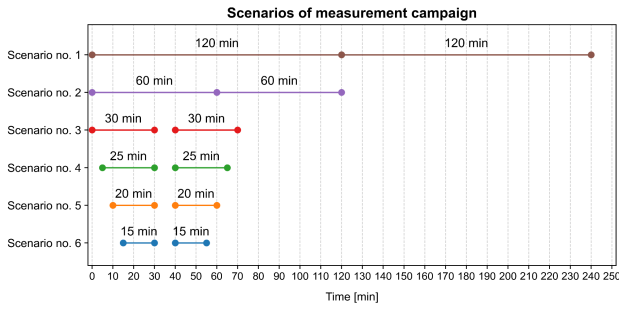


Figure 1: Tested scenarios of measurement campaign durations

nario consists of two measurement sessions at each point, enabling the configuration of independent baselines and the subsequent coordinate adjustment.

Calculations for the reference and test data were carried out using Leica Infinity v.4.2.1 software. In this study, commercial software was used to demonstrate the accuracy level of results obtained in widely available software, without the need to develop custom algorithms dedicated to low-cost receivers. The processing strategies for both campaigns were identical. The post-processing was performed with the double-differencing approach. GNSS observations were processed using precise orbit and clock products provided by the Center for Orbit Determination in Europe (Dach et al., 2024), and antenna calibration models supplied by the National Geodetic Survey (NGS) were applied for all geodetic-grade receivers. Moreover, the elevation mask was set to 10° , while other parameters, such as the ionospheric and tropospheric models, were set to automatic mode. In the applied software, this automatic configuration dynamically selects the appropriate mitigation strategy based on baseline length and observation duration. For short baselines (< 10 km), ionospheric and tropospheric delays are mostly eliminated through double-differencing, the general form of which is expressed as:

$$\Delta\phi_{jk}^{AB} = \Delta\rho_{jk}^{AB} + \Delta T_{jk}^{AB} - \mu\Delta I_{jk}^{AB} + c\Delta\delta_{jk}^{AB} + \lambda\Delta N_{jk}^{AB} + \Delta\epsilon_{jk}^{AB}, \quad (1)$$

where $\Delta\phi_{jk}^{AB}$ is the double-differenced carrier phase observation, $\Delta\rho_{jk}^{AB}$ is the double-differenced geometric range between the receivers (j, k) and the satellites (A, B), ΔT_{jk}^{AB} is the double-differenced tropospheric delay effect, ΔI_{jk}^{AB} is the double-differenced ionospheric delay at the primary frequency, μ is the frequency-dependent ionospheric scaling factor, c is the speed of light in a vacuum, $c\Delta\delta_{jk}^{AB}$ is the double-differenced hardware phase bias, λ is the wavelength, ΔN_{jk}^{AB} is the integer double-differenced phase ambiguity, $\Delta\epsilon_{jk}^{AB}$ represents the double-differenced measurement noise including multipath effects, A and B denote the reference (pivot) satellite and the second satellite, j and k denote the reference receiver and the second receiver.

For longer baselines, standard ionosphere-free combinations ($\phi_{\text{iono-free}}$) and ionospheric modeling are calculated for observation durations exceeding 45 minutes, as follows:

$$\phi_{\text{iono-free}} = \frac{f_1^2 \phi_{L_1} f_2^2 \phi_{L_2}}{f_1^2 - f_2^2}, \quad (2)$$

where f_1 and f_2 denote the frequencies of the L_1 and L_2 signals, ϕ_{L_1} and ϕ_{L_2} are their corresponding carrier phase measurements.

Tropospheric modeling is applied if the duration exceeds 90 minutes, and VMF + GPT2 are automatically used for shorter sessions.

After determining the baselines, a rigorous adjustment of the GNSS observations was performed in two stages, treating the horizontal and vertical network adjustments separately. Only those vectors that achieved “Phase Fixed” status, meaning that their phase

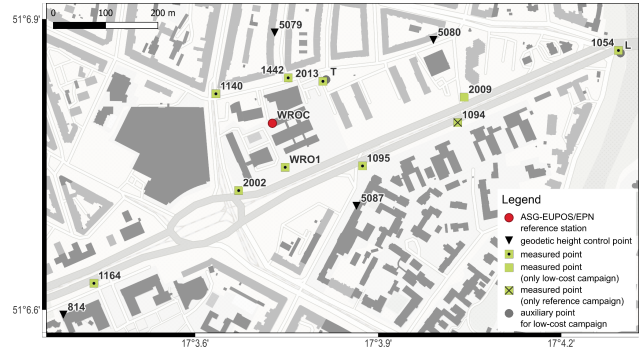


Figure 2: Test area with measurement point locations

ambiguities have been resolved as integer values, were included in the adjustment. The adopted methodology enabled obtaining a final solution consistent with the requirements of the regulations. The horizontal coordinates of the measurement points were determined based on the adjustment of independent GNSS vectors in Leica Infinity.

In this study, point heights were initially derived via GNSS leveling using a quasigeoid model directly within Leica Infinity. To compare these results with a legally compliant approach, an additional test was conducted in which normal height differences were directly adjusted. Thus, the point heights were calculated using the normal height differences obtained after completing the computations of all independent baselines (Regulation, 2021). The calculated height differences were adjusted using C-GEO software, version 8.17.9.20 *Softline Plus* (2024), in accordance with the applicable legal regulations, utilizing the PL-geoid2021-EVRF2007-NH quasigeoid model. For adjustment, only short GNSS baselines were selected. This network was then adjusted in C-GEO software using the least squares method, with reference to four points of the national vertical control network.

2.2 Test area

The measurement area was located in the center of Wrocław near the WROC IGS station belonging to the ASG-EUPOS network. This urban area is characterized by high-rise buildings that limit horizon visibility and dense technical infrastructure prone to satellite signal interference. Selecting such an environment allowed the evaluation of low-cost equipment performance under conditions with a higher risk of GNSS signal distortion. Consequently, the obtained results provide a more realistic basis for assessing the practical applicability of low-cost surveying equipment than tests conducted in open-sky scenarios.

Figure 2 illustrates the distribution of the measurement points, where static GNSS surveying was conducted, together with four vertical control points located on nearby buildings. These locations were chosen to ensure suitable conditions for satellite observations, with good horizon visibility.

Since point 1094 was destroyed between the two measurement campaigns, point 2009 was used instead during the second campaign, and its reference values were taken from an earlier GNSS survey performed with geodetic-grade receivers.

2.3 Benchmark campaign

The benchmark campaign was conducted on 20 May 2024 using high-precision geodetic receivers. The static GNSS survey was performed with nine precision receivers – five manufactured by Trimble and four by Leica. The benchmark campaign consisted of two approximately 1-hour observation sessions, separated by a 10-minute break. No receivers were exchanged be-

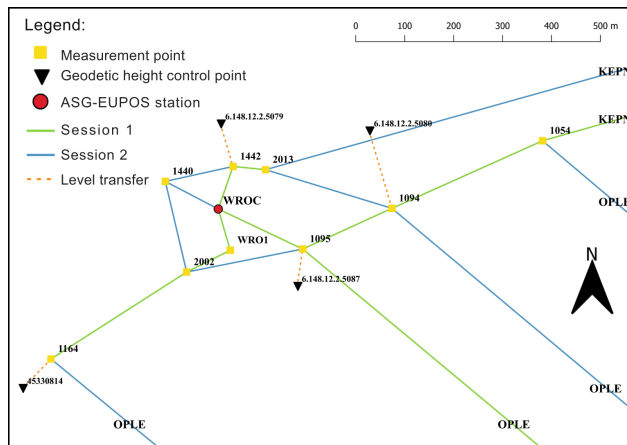


Figure 3: Network of independent GNSS vectors – reference campaign

tween survey points across sessions. During the campaign, a variety of multi-frequency and multi-constellation geodetic antennas were deployed at the measurement points. These included dual-frequency GPS/GLONASS models (Leica LEIGS08PLUS and Trimble TRMR6/TRMR6-2), triple-frequency GPS/GLONASS/Galileo models (Leica LEIGS14 and Trimble TRMR10/TRMR12), as well as a fully multi-GNSS receiver (Leica LEIGS18) capable of tracking GPS, GLONASS, Galileo, and BeiDou signals across all primary frequency bands (including L5, E6, and B3).

Figure 3 shows the network of independent GNSS vectors designed for processing. The geometric structure of the network was tied to three ASG-EUPOS reference stations – WROC, OPLE, and KEPN – as well as four points from the national vertical control network. For data collected during the first observation session, ten baselines were determined, while nine baselines were computed from the second session.

2.4 Experimental campaign

The low-cost measurement setup (Figure 4) used in the survey comprised a custom-built receiver equipped with proprietary software for its operation, together with a multi-GNSS low-cost ArduSimple antenna (AS-ANT3B-CAL-L1256-SMATNC-01). The custom-built receiver was based on a u-blox ZED-F9P high-precision multi-band GNSS module connected to a Raspberry Pi 3B+ microcomputer, which managed data logging and system operations. The receiver operation was controlled by a custom Python script designed to automatically capture and store multi-frequency carrier-phase and code observations directly into the standardized RINEX 3.04. The u-blox ZED-F9P module is widely classified in GNSS literature as an affordable, mass-market receiver. This classification is justified not only by its significantly lower price point compared to geodetic-grade instruments but also by its technical characteristics, such as a compact, low-power OEM board design tailored for mass-market integration rather than proprietary high-end geodetic architectures. The experimental survey was conducted on 5 August 2024 at nine points, eight of which were identical to those used in the benchmark campaign.

Processing data from low-cost GNSS receivers involves several critical challenges, particularly regarding cycle slips and multipath effects. The RINEX observation data from 5 hours of measurements were processed with the GNSS Data Analysis tool (Gao et al., 2025) to examine the problem related to GNSS observation accuracy when using survey-grade (Leica, Trimble) and low-cost u-blox GNSS receivers (Figure 5). Despite the lower epoch completeness of the low-cost receiver compared to that of the other receivers, the observation completeness was achieved on the same level. However,



Figure 4: Equipment used in the experimental measurement: GNSS antenna and low-cost GNSS receiver

there were substantial differences observed in the cycle slip rate and multipath value. During the campaign, low-cost u-blox GNSS receivers were characterised with significantly higher cycle slip rates and mean multipath than survey-grade receivers used in the study.

Thus to ensure the connection of the established geodetic control network with distant ASG-EUPOS reference stations, two multi-frequency geodetic receivers – Leica GS18 and Trimble R12 – were included in the survey, following methodology of Kazmierski et al. (2023). Those high-end receivers served an auxiliary function, and their coordinates were not determined. The measurements were carried out continuously during a single approximately 5-hour measurement session. Such a long observation session made it possible to conduct subsequent experiments analyzing the impact of session length on the obtained results.

The computational work was divided into several stages, consisting of testing different strategies for planning the survey campaign. Measurement sessions of a specified duration were extracted from the observational data recorded in RINEX format using GFZRN software v. 1.15-8044 (Nischan, 2016). During the post-processing stage, the network in each considered scenario was connected to a minimum of three ASG-EUPOS reference stations and four benchmarks from the national vertical control network. The network was referenced to four ASG-EUPOS reference stations WROC, OPLE, LEGN and KROT. The connection to the WROC station was realized using low-cost GNSS receivers located nearby. Connections to the remaining ASG-EUPOS reference stations (OPLE, LEGN, and KROT) were established using geodetic receivers due to the long distances involved. All GNSS vectors included in the rigorous adjustment were in the “Phase Fixed” status. Where possible, a constant vector configuration was maintained within the network consistent with the configuration used in the reference campaign. Calculations were performed with the same processing settings as in the benchmark campaign. The only exception concerned the unavailability of NGS antenna calibration files for low-cost equipment. The corresponding procedure and analyses are described in the next section. For test campaign, particular attention was given to the following aspects:

- analysis of available information regarding the antenna reference point (ARP) offsets of the low-cost ArduSimple antennas,
- selection of the duration of measurement sessions so as to minimize fieldwork time while maintaining the required accuracy of data processing.

2.5 Low-cost antenna offsets

One of the most important factors that influence positioning accuracy in precise measurements is the antenna type. Currently, most low-cost antennas available on the market do not have official calibration data. The use of information regarding the phase center offset (PCO) of an antenna relative to its physical ARP is essential. The data, contained in ANTEX files, help users to minimize position determination errors during measurement (Teunissen et al., 2017). However, it should be emphasized that this is not the only challenge when working with low-cost antennas. An equally significant issue is the effect of the satellite signal multipath, which can considerably degrade positioning accuracy depending on satellite geometry and

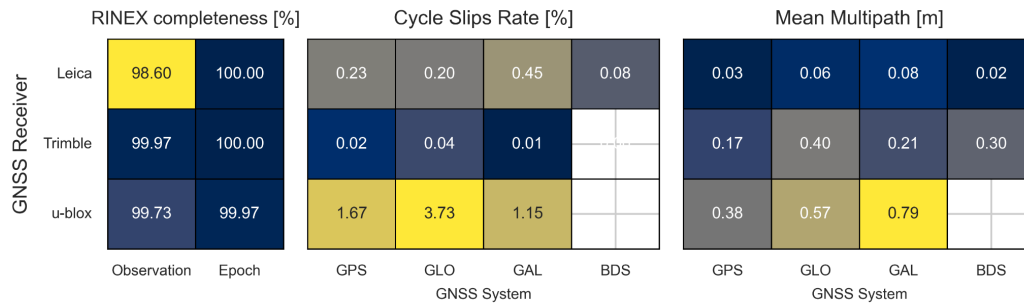


Figure 5: Quality parameters of GNSS data for tested receivers: RINEX completeness, cycle slip rate, and mean multipath effect

Table 1: Tested variants with different vertical ARP offsets of ArduSimple antennas

Variant no.	Assumptions of the calculation variant
Variant 1	No consideration of ARP offsets – calculations performed without ANTEX files
Variant 2	ANTEX file containing the first set of ARP offsets, obtained from the literature (Marut et al., 2024)
Variant 3	ANTEX file containing the second set of ARP offsets, obtained from the literature (Marut et al., 2024)
Variant 4	ANTEX file containing ARP offset values calculated as the average of variants 2 and 3
Variant 5	ANTEX file containing ARP offset information from manufacturer data described for ArduSimple antennas

measurement conditions (Krzan et al., 2024). This phenomenon directly affects the phase ambiguity fixing ratio. Studies have shown that this ratio can be up to approximately 20% lower when using a low-cost antenna compared to a geodetic-grade antenna (Hamza et al., 2023).

At the time of processing the experimental survey results, the ArduSimple antennas used during field measurements did not have official ANTEX files. Considering the available materials and current knowledge on ARP offsets for ArduSimple antennas, it was decided to perform computations using various offset configurations. The processing and adjustment of the GNSS vector network were carried out using five configurations included in Table 1. The available PCO information referred only to the vertical (UP) component. The horizontal components were assigned a value of zero, as no verified offsets were available for these directions. In the first variant, the computations were performed without applying ARP corrections in order to assess the impact of their exclusion on the results. The second and third variants included vertical PCO values determined experimentally for two individual ArduSimple antennas. These results reflect the characteristic PCO values of a single antenna. The computations were performed relatively to the WROC reference station using Bernese software (Marut et al., 2024). The fourth approach assumed an average of the values derived from the second and third variants. In the fifth configuration the vertical ARP correction provided by the manufacturer and indicated on the antenna label was tested.

The vertical PCO values for each frequency entered into the Leica Infinity software are presented in Table 2. The analysis of the five variants made it possible to assess the impact of different strategies for including or excluding PCO values on the accuracy of results obtained using low-cost measurement sets. The analysis of offset information was carried out on the entire dataset of observational

Table 2: Used vertical PCO values

Variant no.	UP component of PCO values for frequency [mm]					
	GPS		GLONASS		Galileo	
	L1	L2	G1	G2	E1	E5b
Variant 1	—	—	—	—	—	—
Variant 2	48.30	38.20	48.50	41.30	47.60	32.00
Variant 3	51.00	51.10	51.80	52.30	50.30	47.60
Variant 4	49.65	44.65	50.15	46.80	48.95	39.80
Variant 5	58.00	52.00	58.00	52.00	58.00	52.00

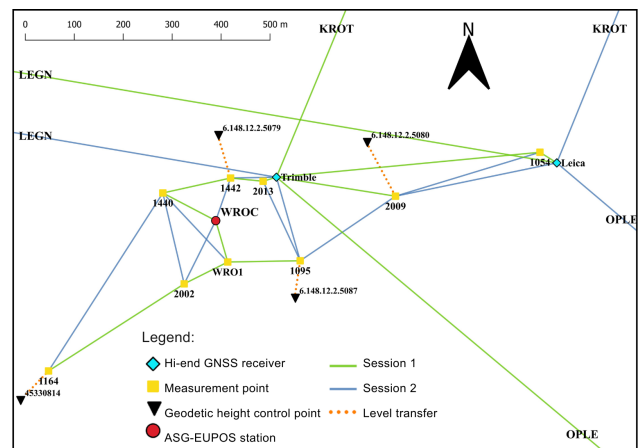


Figure 6: Network of calculated independent GNSS vectors – low-cost GNSS campaign, 2-hour sessions

records collected during the measurement campaign. From this dataset, two measurement sessions of approximately 2 hours each were extracted.

The computation strategy was identical to that used for the benchmark campaign. To enhance the reliability of the results for the five considered variants, the geometric configuration of the independent GNSS vector network was kept identical during the calculations (Figure 6). The computations were performed on baselines between the same survey points, maintaining identical start and end points for each GNSS vector. No significant issues were observed during the computation of baselines using low-cost GNSS receivers. The rigorous adjustment of the established geodetic control network was performed for each of the five PCO variants in a similar, two-step manner as during the processing of the benchmark campaign.

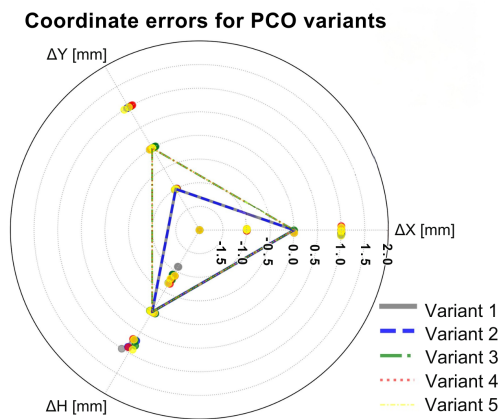


Figure 7: Deviations in X, Y and H coordinates with median for the analyzed measurement points, corresponding to each applied PCO variant for low-cost GNSS measurements

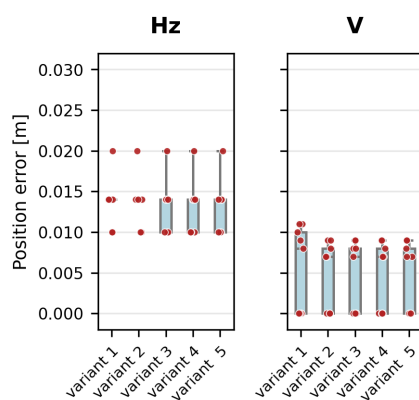


Figure 8: Horizontal (HZ) and vertical (V) positioning accuracy for 2-hour observation sessions under different PCO variants applied to low-cost GNSS observations

3 Results

The obtained results made it possible to identify the conditions under which low-cost GNSS receivers can provide reliable geodetic data while minimizing the total measurement time.

3.1 Analysis of ARP offsets

The ARP offset analysis was carried out for low-cost GNSS receivers using the full dataset, consisting of two 2-hour sessions, processed according to five different variants described in section 2.5. To assess the accuracy of the determined point positions, the obtained coordinates were compared with those from the benchmark campaign. Position errors (Figure 8) for the horizontal (HZ) and vertical (V) components were calculated based on the coordinate differences ΔX , ΔY and ΔH computed relative to the reference coordinates (Figure 7). For four points, the height error was zero because they served as benchmarks for height referencing. The elevations for these points were transferred from nearby geodetic benchmarks using geometric levelling. Their heights, just like the X and Y coordinates of the ASG-EUPOS reference stations, were assumed to be error-free. The number of points subjected to height determination was limited, as four points were required by regulations to serve as vertical references. The remaining number of available points was constrained by the limited number of low-cost GNSS receivers participating in the field campaign.

The performed computations and obtained results confirmed

the significant impact of ARP offsets on measurement accuracy. Taking these offsets into account is essential when establishing a geodetic control network. The analysis of the acquired height errors of the measurement points showed that less accurate results were achieved in variant 1 that did not include any ARP offsets. In this variant, the height errors for two measurement points exceeded the assumed 0.01 m threshold. In the remaining four analyzed variants, the positioning accuracy in both the horizontal and vertical components was within the threshold.

Considering the collected results, variant 4 was selected for the subsequent stages of the research. It produced outcomes comparable or even better than those of the other variants. Although variant 2 gave identical results, it was not chosen for further analysis because the values used in this variant were specific to a single antenna (Marut et al., 2024). Since such information was not available for all antennas used, it was considered more reliable to apply averaged values determined for two specimens of the same antenna model. Variant 5 was rejected because its PCO values deviated significantly from the experimental results and assumed identical offsets for both frequencies.

3.2 Influence of shortening the measurement sessions

During the second stage of the analysis, attention was focused on determining the optimal duration of the observation session with low-cost GNSS equipment. The objective of this part of the study was to identify the shortest session time that would still ensure the required accuracy of point positioning. Tests were conducted using data from the low-cost GNSS campaign, which were divided into shorter sessions using GFZRNX software into pairs of 60-, 30-, 25-, 20- and 15-minute sessions (Figure 1).

The independent GNSS vector network using low-cost GNSS receivers for the shorter observation sessions was planned using the layout from the first campaign. Baselines were initially computed between the same measurement points, with each GNSS vector retaining identical start and end coordinates. If necessary, the network of independent GNSS vectors was adjusted to meet the required horizontal and vertical positional accuracies. It was assumed in the analyses that the field observations were carried out in two independent time intervals. Four ASG-EUPOS stations were used again for horizontal referencing and four benchmarks located in the measurement area.

The scenario with 60-minute observation sessions was also conducted without any breaks between sessions. No difficulties were found in obtaining a “Phase Fixed” solution type for any of the GNSS vectors during the baseline processing. In the next stage, the observation sessions were shortened to 30 minutes with breaks of several minutes introduced between sessions to increase the variation in the geometry of the observed satellites. Analyses showed that a 10-minute break enabled the formation of a GNSS vector network that met the accuracy requirements in both horizontal and vertical components. The next measurement scenario consisted of two 25-minute observation sessions separated by a 10-minute break. Baseline processing in this configuration was completed without significant difficulties, and verification confirmed that the errors in determining the heights and horizontal positions did not exceed the applicable threshold. The results obtained from 20-minute sessions also demonstrated that, even with such a short data collection period, it was possible to correctly establish a geodetic control network at the required accuracy level. As in the previous cases, introducing a 10-minute break between sessions was necessary to ensure sufficient variation in satellite geometry and, consequently, accurate results of the rigorous adjustment.

The post-processing results from the 15-minute sessions with a 10-minute break showed that the GNSS vector network did not meet the required accuracy for determining point positions. Most of the vectors computed for point WRO1 did not achieve a “Phase Fixed” status. The insufficient accuracy is mostly related to difficulties in

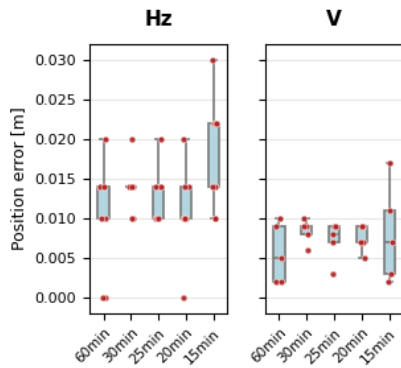


Figure 9: Horizontal (HZ) and vertical (V) positioning accuracy for 60-, 30-, 25-, 20- and 15-minute observation sessions for low-cost GNSS measurements

determining vectors between low-cost GNSS receivers. The most significant issues concerned point WRO1, located among tall trees and buildings on its southern and south-western horizon, which significantly degraded the quality of the recorded observations and prevented their further use in the adjustment process. Moreover, the results for two other measurement points did not achieve the required accuracy, with height errors exceeding 0.01 m. However, the horizontal positions for all points were determined correctly, with errors well below 0.07 m.

Figure 9 presents the distribution of horizontal (HZ) and vertical (V) position errors for various observation session durations. In the horizontal component, the results obtained for 60-, 30-, 25- and 20-minute sessions are comparable, whereas a clear deterioration is observed for the 15-minute sessions, reflected in both increased dispersion and larger individual errors. In the vertical component, the differences between the scenarios are more pronounced. The spread of errors tends to increase systematically as the observation time decreases. The 15-minute scenario shows the highest variability and the largest individual deviations for measurement points, confirming a reduction in vertical accuracy for the shortest observation sessions.

Analyses of the different session lengths demonstrated that establishing a geodetic control network using the static GNSS technique with a set of low-cost GNSS receivers (supplemented by geodetic-grade equipment to provide long baselines) is feasible within a relatively short time. The shortest effective configuration allowed all fieldwork to be completed within 50 minutes (2×20 -minute observations with a 10-minute break). The results indicate that 20-minute sessions provide a reasonable compromise between measurement efficiency and positioning accuracy. This approach minimized the total field time, ensured appropriate data quality and delivered the required accuracy of the final results. Reducing the observation duration below 20 minutes led to a noticeable deterioration in both horizontal and vertical accuracy, with the effect being more pronounced in the vertical component.

Furthermore, the analyses showed that changing the duration of observation sessions caused only minor variations in the configuration of the independent GNSS vector network. These differences primarily affected the long baselines, which was related to difficulties in connecting the geodetic network to the ASG-EUPOS reference stations. The long GNSS vectors were often associated with larger errors, which required their removal and replacement with alternative vectors during the rigorous adjustment. The internal configuration of the computed baselines remained stable across the tested scenarios. The configuration with sessions shorter than 20 minutes did not meet the required accuracy standards and was therefore excluded from further analysis.

During post-processing, a total of 26 to 28 independent GNSS

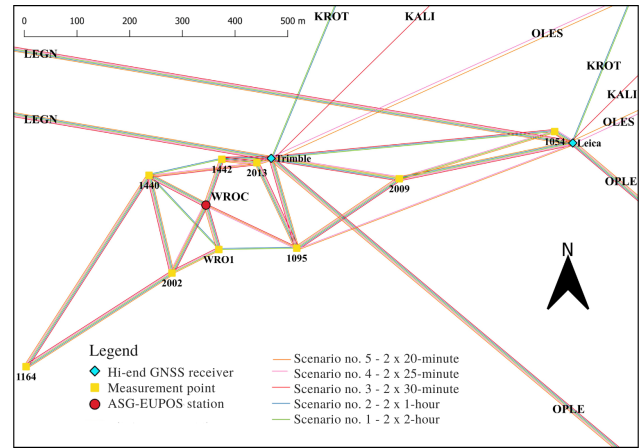


Figure 10: GNSS vector layout for different measurement session durations in the low-cost GNSS campaigns

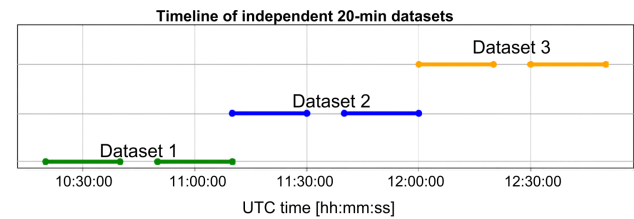


Figure 11: Selection of independent datasets used in the 20-minute session analysis, derived from the low-cost GNSS campaign

vectors were successfully determined from the two sessions for the effective scenarios. Figure 10 illustrates the evolution of all applied vector configurations. It indicates that most connections between measurement points are consistent and that the network was only minimally affected by changes in session duration. This is reflected in the overall thickness of the trace formed by the calculated GNSS vectors on Figure 11. The greatest differences in the internal structure of the network were observed near point WRO1, where significant horizon obstructions from surrounding trees and nearby high-rise buildings degraded the recorded observations. As a result, the baselines associated with this point were modified because the required height accuracy was not achieved.

The findings of the study demonstrate that when using low-cost GNSS receivers, it is essential to assess field conditions in advance and to appropriately adjust the duration of observation sessions. Satellite signal disturbances caused by the surrounding environment can significantly affect data quality. However, their impact can be mitigated by collecting sufficiently long observation datasets and introducing suitable breaks between observation sessions.

3.3 Extended analyses for 20-minute datasets

Due to the use of low-cost GNSS receivers in the experimental measurements, it was necessary to verify whether 20-minute observation sessions were sufficient to obtain data of adequate quality. The aim of the extended analysis was to assess whether the previously obtained favorable results could be reliably reproduced. For this purpose, two additional independent datasets were extracted from the collected observations. Consequently, the evaluation of the measurement strategy based on 20-minute sessions was carried out using three selected independent datasets (Figure 11).

The first issues were observed in the ambiguity resolution process for baselines between low-cost GNSS receivers. These issues occurred only in isolated cases, in which the GNSS vectors did not achieve a “Phase Fixed” solution, making them inappropriate for

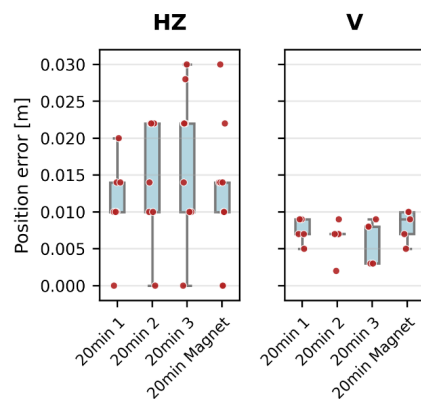


Figure 12: Horizontal (HZ) and vertical (V) positioning accuracy for specific scenarios of 20-minute observation sessions extracted from low-cost GNSS campaigns

inclusion in the rigorous adjustment, which usually does not occur for geodetic-grade equipment. Nevertheless, these problems have no significant impact on the final results. Despite the limited number of samples, the findings confirmed that establishing a geodetic control network using the static GNSS method with 20-minute sessions is feasible. For all analyzed datasets, it was possible to compute and correctly adjust the network of independent GNSS vectors. Figure 12 illustrates that in both additional datasets, the height determination error did not exceed 0.01 m, while horizontal positions were determined with an accuracy better than 0.07 m.

To further verify the robustness of the collected data, an additional analysis was also performed using MAGNET Tools v.7.3.0 software. This analysis involved satellite observations from one of the 20-minute observation sessions and the same configuration of independent GNSS vectors as in Leica Infinity software, without examining alternative baseline configurations. The objective was solely to verify whether, under an identical network configuration, the satellite observations could be correctly adjusted in independent software. The adjustment procedure followed the same principles as in Leica Infinity software. The obtained results were compared with reference values and confirmed to meet the required accuracy standards (Figure 12). Point heights were determined with an accuracy better than 0.01 m, and horizontal coordinates with errors not exceeding 0.03 m.

Considering the results obtained from computations in Leica Infinity and MAGNET Tools, the scenario with 20-minute observation sessions was identified as the most advantageous, taking into account both the duration of fieldwork and the achieved accuracy. For comparison of effectiveness, the heights were calculated in two ways: for one of the datasets, in accordance with national regulations, by adjusting the height differences projected onto the quasigeoid in C-GEO; and for the others, by adjusting calculated baselines in Leica Infinity and deriving normal heights using the quasigeoid model. Both methods utilized a levelling network composed exclusively of short GNSS vectors (Figure 13).

Discrepancies between the heights with both approaches did not exceed 0.003 m, indicating a high level of agreement between the two methods. Comparison with the reference values (Figure 14) confirmed that the data processed in C-GEO also met the required accuracy, with errors for none of the measurement points exceeding 0.01 m. The obtained results pointed to strong consistency between the two approaches and confirmed the accuracy of computations performed in Leica Infinity relative to C-GEO.

Taking into account the objectives of the conducted analyses, the additional computations performed using independent software confirmed the effectiveness of the 20-minute measurement scenarios for planning survey campaigns. With proper selection of

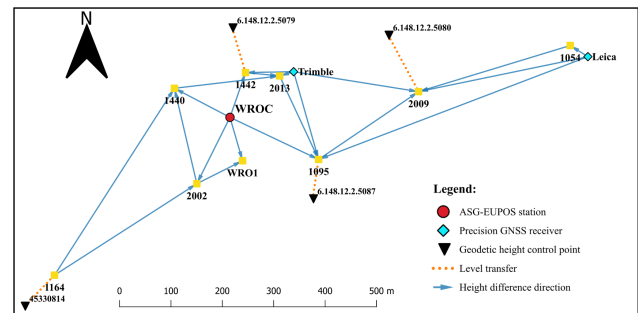


Figure 13: Levelling GNSS network based on 20-minute measurement sessions

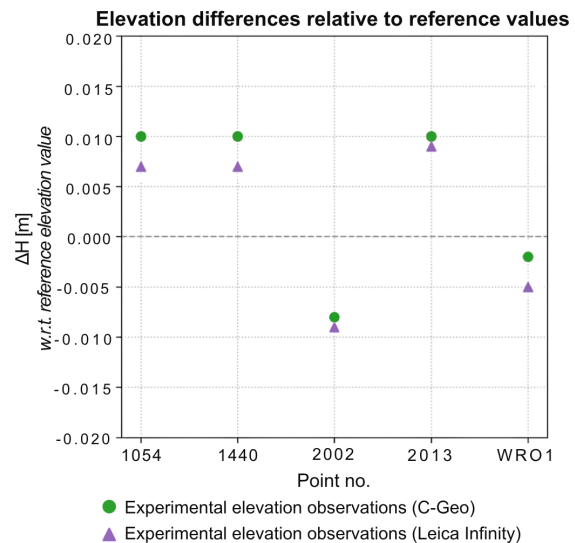


Figure 14: Elevation differences relative to the reference values for the analyzed measurement points using C-GEO and Leica Infinity software

independent GNSS vectors during processing, it is highly probable that the required accuracy is achieved. This approach reduces fieldwork time while maintaining adequate data quality. The obtained results confirm the practical suitability of low-cost GNSS receivers for typical geodetic tasks, such as those related to the establishment of geodetic control networks.

4 Conclusions

Technological development and the growing capabilities of global navigation satellite systems make it possible to establish geodetic control networks using low-cost GNSS receivers. Despite the promising results of experimental measurements, it is important to remain aware of the limitations of such devices, which may influence the accuracy of positioning. The greatest challenges concern heights determination, especially when short observation sessions are used. Accurate horizontal positioning, with errors below 0.07 m, can be achieved even with 15-minute sessions. In the presented tests, the horizontal accuracy (under 0.03 m) was found to be lower than the vertical accuracy (under 0.01 m). While this relation is typically reversed in standard GNSS positioning, this specific outcome can be explained by two main factors. First, it may be partially related to the limited number of check points for which vertical accuracy could be rigorously evaluated. Second, and more importantly, a significant influence is attributed to the short vertical reference vectors linking the network to the physical reference benchmarks. This referencing scheme was strictly necessary to comply with tech-

nical regulations, which mandate that vertical control points must be evenly distributed across the entire study area.

The field experiment demonstrated that the requirements for establishing geodetic control networks can be met using 20-minute observation sessions. When planning a measurement campaign based on this approach, it is recommended to conduct two observation sessions separated by a 10-minute break to alter the satellite geometry. This configuration allows the entire measurement to be completed within 50 minutes, reducing fieldwork time and maintaining high data quality. Datasets collected in this manner do not cause difficulties during post-processing, and the computed GNSS vectors typically achieve a “Phase Fixed” solution without major issues.

The antennas used during field measurements play a crucial role when working with low-cost GNSS receivers. To achieve the accuracy required for establishing a vertical geodetic control network using satellite levelling, it is essential to consider the ARP offsets of the antennas used during the measurements. Incorporating calibration data significantly improved the final results, whereas omitting these corrections led to the height determination errors exceeding 0.01 m. The location and surroundings of the measurement points are also important. Terrain obstacles such as trees or tall buildings adversely affect the quality of observations, particularly during short measurement sessions. As a consequence, the obtained results may fail to meet the required accuracy standards. Additionally, when processing such datasets, issues may arise with the solution status of the computed baselines. These effects were particularly evident for observations collected at point WRO1, where the heavily obstructed horizon combined with 15-minute sessions caused the greatest difficulties and resulted in height errors exceeding the allowable limits.

Overall, low-cost GNSS receivers can be successfully used to establish geodetic control networks using the static method. The obtained accuracies were below 0.03 m in horizontal position and below 0.01 in height. They met the accuracy requirements specified in the legal regulations. Software selection for network adjustment has minor impact on results, demonstrating that data from low-cost GNSS receivers can be effectively processed using any standard satellite-based network adjustment software. Based on the conducted analyses, a strategy involving two 20-minute measurement sessions is recommended, as it provides a practical compromise between measurement duration and the quality of the final results. When planning a measurement campaign, it is advisable to supplement observations with data from geodetic-grade receivers to ensure proper connection to distant CORS reference stations (in Poland: ASG-EUPOS). To achieve a more comprehensive assessment of how 20-minute measurement sessions influence the quality of the results, further analyses using this measurement scenario would be beneficial. Such studies would enhance the reliability of the presented findings through statistical evaluation based on a larger dataset. This direction may serve as a foundation for future research conducted as part of a separate experiment.

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