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ORIGINAL ARTICLE

Evaluation of the suitability of static GNSS and free station methods for establishing construction control networks in a high-rise building: A case study

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Abstract

This paper presents a case study comparing the Free Station method using a Leica MS60 total station and the static GNSS method using Topcon Hiper HR receivers for establishing construction control points during the construction of a 10-storey residential building in Kielce, Poland. The comparison was performed for selected points located on the ground level and on an upper storey. The results show that the coordinate agreement between the two solutions differed between the analysed construction levels. The study presents the observation procedure, GNSS processing strategy, internal precision indicators and coordinate differences obtained for the investigated points. The results are discussed in relation to observation geometry, control point accessibility and practical conditions in engineering surveying. The paper supports the complementary use of Free Station and static GNSS methods in construction control networks when both terrestrial and satellite observation conditions are suitable.

Keywords: construction control network, static GNSS, free station, total station, coordinate differences, high-rise building, case study

1 Introduction

High-rise construction requires reliable geodetic control networks because transferring design axes and control points between successive storeys directly affects the structure's geometric consistency and the repeatability of setting-out operations (da Silva et al., 2017; Novomlynets et al., 2022).

The growing height and complexity of contemporary buildings increase the importance of precise geodetic support, especially for maintaining geometric consistency, verticality control and reliable transfer of construction axes during successive construction stages (da Silva et al., 2017; Novomlynets et al., 2022; Cheng et al., 2023; Correa Muñoz and Cerón-Calderón, 2018).

In Poland, high-rise construction is developing mainly in large urban areas. Buildings such as Varso Tower in Warsaw show that construction projects increasingly require surveying procedures that maintain consistency between the design coordinate system, the external control network, and the internal control points transferred to higher storeys.

From a surveying perspective, the main difficulty is that a method that performs well at the initial stage of construction may become less favourable as building height increases. This is caused by changes in observation geometry, limited visibility of terrestrial control points and the need to repeatedly transfer the construction control network to higher storeys (Correa Muñoz and Cerón-Calderón, 2018).

The construction control network usually consists of external reference points established outside or around the building and internal control points transferred to individual storeys for direct setting-out of structural elements.

Previous studies, surveying textbooks, and practical engineering experience indicate that no universal measurement method suits all construction stages and site conditions (Ghilani and Wolf, 2012; Uren and Price, 2010; Kavanagh and Slattery, 2014; Krawczyk, 2023; Nistor et al., 2024). Total station and Free Station techniques provide local control. They are directly connected to setting-out operations, while static GNSS is useful where sufficient sky visibility is available, and coordinates can be determined through network-based or baseline post-processing. For reliable construction control, stable reference points, good observation geometry, and repeated

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accuracy checks remain essential.

Hybrid surveying strategies combining total station observations and GNSS positioning are therefore increasingly considered in high-rise construction, engineering control networks and structural monitoring. This approach is particularly useful when local setting-out precision must be connected to an external geodetic reference frame (Yuan et al., 2024; Ali et al., 2016; Zhou et al., 2025).

The literature includes examples of combined total station and GNSS applications for monitoring tall buildings and controlling construction geometry (da Silva et al., 2017; Cheng et al., 2023; Yuan et al., 2024). Other studies have analysed the precision and reliability of static GNSS in engineering networks (Correa Muñoz and Cerón-Calderón, 2018; Krawczyk, 2023; Nistor et al., 2024).

This paper presents a case study in which both methods were applied to selected construction control points of one high-rise residential building and compared using coordinate differences obtained at two construction levels.

The objective of the paper is to assess, for the investigated case study, how coordinate agreement between the Free Station and static GNSS solutions changes between the ground level and an upper storey, and to identify practical factors to consider when selecting a measurement method for construction control networks in high-rise buildings.

2 Methodology for establishing a construction control network

This study analysed the construction control network using two surveying approaches: the Free Station method based on terrestrial angular and distance observations, and a static GNSS method based on network post-processing. This methodological section describes the observation geometry, the origin of the control points, the processing strategy and the precision indicators used in the comparison. It also distinguishes internal precision estimates from independent accuracy assessment and clarifies the practical limitations of the case study.

In this paper, coordinate differences denote differences between coordinates from the Free Station and GNSS solutions. We use standard deviations reported by the instrument or GNSS processing software only as internal precision indicators for the respective solutions.

2.1 Free Station method and terrestrial observation procedure

We used the Free Station method to determine the positions of selected construction control points from terrestrial observations to previously established reference points. The method is based on observing horizontal directions, vertical or zenith angles, and slope distances from an unknown station to points with known coordinates. Its reliability depends on the number, spatial distribution and stability of reference points, as well as on instrument set-up and observation procedure (Ghilani and Wolf, 2012; Uren and Price, 2010; Kavanagh and Slattery, 2014; Ali et al., 2016).

For each Free Station setup, we observed horizontal directions, zenith angles and slope distances to six reference points. The observations were processed in the instrument software as a three-dimensional Free Station solution. The instrument report provided coordinate residuals for each reference point and standard deviations of the estimated station coordinates. We performed the analyses in Face I only and without repeated observation series. This limitation is stated because two-face observations and repeated series can reduce selected instrumental and systematic effects. For clarity in the revised manuscript, the compared construction control points are denoted by unified identifiers P1–P4; the original field labels are retained only in measurement documentation. Table 1 summarises the internal precision indicators from the Free Station reports. Figs. 1 and 2 show the general Free Station observation concept and examples of construction targets, respectively.

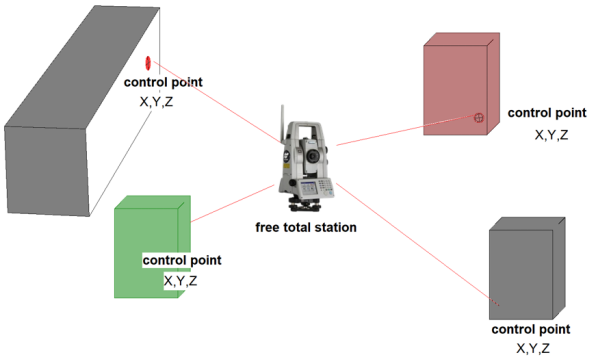


Figure 1: Free Station measurement concept

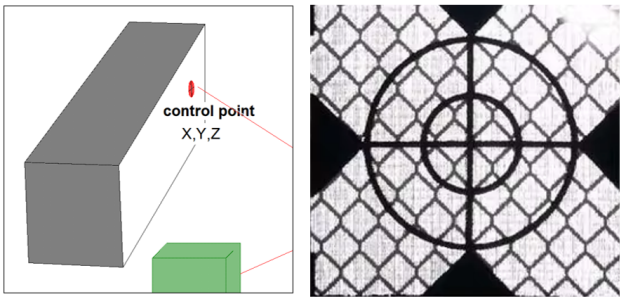


Figure 2: Examples of targets used for construction control points

2.2 Static GNSS method and network-based processing strategy

We performed static GNSS observations on selected construction control points using Topcon Hiper HR multi-constellation receivers. The observation time for each analysed point was approximately one hour. In engineering applications, static GNSS can be processed using several strategies, including network-based processing, single-baseline processing and precise point positioning. In this study, we processed the static GNSS data using Leica Spider Business Centre / SmartNet XPOS in network-based post-processing mode (Cheng et al., 2023; Correa Muñoz and Cerón-Calderón, 2018; Krawczyk, 2023; Nistor et al., 2024; Yuan et al., 2024). The processing report indicates a Phase Fixed solution, meaning the processed baseline solutions fixed carrier-phase ambiguities. The processing used GPS, GLONASS, Galileo and BeiDou observations, an elevation mask of 10 degrees, broadcast ephemerides, a VMF tropospheric model and a computed ionospheric model. In the processing software, the term computed ionospheric model means that ionospheric corrections were estimated internally from the available multi-frequency GNSS observations rather than introduced as an external fixed model. The frequency set used in the submitted processing report included L1, L2 and L5, and the sampling interval was 5 s.

The example processing report for point 30904 shows that the observation started at 16:52:16 and ended at 17:48:21 on 3 September 2025. Point 30904 is used only as an example of the GNSS processing report and processing-parameter documentation. The Cartesian coordinate standard deviations reported for this example were SD_X = 0.0038 m, SD_Y = 0.0028 m and SD_Z = 0.0047 m. Table 2 reports these values only as internal processing-quality indicators. Figs. 3 and 4 illustrate the static GNSS field observation and the reference-station configuration, respectively, while Table 2 sum-

Table 1: Precision indicators of Free Station solutions from Leica MS60 reports

Point	Storey	No. of reference points	Sigma X [m]	Sigma Y [m]	Sigma H [m]	Sigma Hz orient. [gon]
4500	upper storey	6	0.003	0.004	0.001	0.0011
4501	upper storey	6	0.005	0.005	0.001	0.0017
5500	ground level	6	0.001	0.002	0.001	0.0004
5502	ground level	6	0.001	0.001	0.001	0.0003

marizes the baseline lengths. The internal 3D precision indicator. is a processing-software quality indicator derived from the three coordinate components of the baseline solution. It is reported only as an internal precision measure and is not used as an independent accuracy reference.

Table 2. Baseline lengths and internal 3D baseline precision indicators for the example GNSS solution of point 30904.

In the network-based GNSS processing used in this study, the coordinates of the investigated construction control points were computed with reference to surrounding permanent GNSS stations. The stability and configuration of reference stations are important because they directly affect the quality of the derived coordinate solution (Krawczyk, 2023; Nistor et al., 2024).

We compared the Free Station and GNSS methods using coordinate differences calculated for the unified point identifiers P1–P4. The unified numbering scheme is used throughout the results tables to avoid mixing field labels from the Free Station and GNSS processing reports.

3 Measurement procedures and results

The experimental comparison was performed at four control points across two construction levels of the investigated residential building. To avoid ambiguity between original field labels and GNSS processing labels, the manuscript denotes the analysed points as P1–P4. Points P1 and P2 are on the ground storey, while points P3 and P4 are on the upper storey under investigation. The original point identifiers from the field reports were not used as primary point numbers in the results tables. We obtained the Free Station coordinates from single Face I observations using the Leica MS60 total station. No repeated observation series were performed. The static GNSS coordinates were obtained from one-hour sessions processed using the network-based strategy described in Section 2.2 Figs. 5 and 6 illustrate the range of application of the Free Station method and the investigated building, respectively.

Repeatability is crucial in high-rise construction. Generally, there are two phases when it comes to accuracy. The first is when the building is fitted within the plot boundaries based on the construction design, and the second is when the same design points are replicated on individual storeys, at which point we analyse repeatability. In this way, we are dealing with two different measurement accuracies. The first is centimetre accuracy, while the second is millimetre accuracy.

We performed measurements on a 10-storey residential building in Kielce, Poland. The objective was to compare the coordinate agreement between selected control points determined by the Free Station method and by network-based static GNSS post-processing. The building was surveyed during construction, and the analysed points were located at the ground level and on the upper storey under investigation (Figure 9). Figs. 7 and 8 show construction control point stabilization and the static GNSS observation setup , respectively.

The Free Station coordinates were obtained using the Leica MS60 total station and six reference points from the construction control network. The static GNSS coordinates were obtained from approximately one-hour observations processed using the network-based strategy described in Section 2.2. The comparison used coordinate differences for corresponding points rather than absolute accuracy errors.

The analysed GNSS solutions had fixed carrier-phase ambiguities and were processed using five reference stations. We interpreted the reported standard deviations as internal precision estimates of the GNSS solution. Table 4 summarises coordinate differences between the GNSS and Free Station solutions. The horizontal coordinate differences between the GNSS and Free Station solutions ranged from 0.004 m to 0.012 m. At the ground storey, the differences were 0.007 m and 0.012 m. At the upper investigated storey, the differences were 0.005 m and 0.004 m. In this specific case study, the mean horizontal difference decreased from 9.5 mm at the ground storey to 4.5 mm at the upper investigated storey, and the RMS value decreased from 9.8 mm to 4.5 mm.

A formal statistical significance test was not applied because only two points were available at each level and no repeated observation series were performed. Therefore, the results are limited to descriptive statistics and practical comparisons of coordinate agreement. Figure 10 presents an example of the GNSS coordinate computation report used to document the processing strategy. Table 3 lists Free Station coordinate estimates and internal precision indicators.

Figs. 11 and 12 illustrate coordinate differences for the ground-storey and upper-storey points, respectively.

4 Discussion

This case study compares coordinate agreement between two surveying approaches: the Free Station method and network-based static GNSS post-processing. The comparison covered four unified control points at two construction levels.

The results section reports coordinate differences between the two methods and internal precision estimates from the instrument or GNSS processing software. The software-derived standard deviations describe each solution's internal precision, whereas the coordinate differences describe agreement between the two methods.

The comparison at ground level and the upper storey showed smaller horizontal coordinate differences at the upper storey. For the investigated points, the horizontal difference between the GNSS and Free Station solutions was approximately 7–12 mm at the ground level and approximately 4–5 mm at the upper storey. This indicates that, in this case study, agreement between the two methods increased at the upper storey.

The behaviour observed for the Free Station solution may be related to the geometry of terrestrial observations. The Free Station method depends directly on the distribution, visibility and stability of the reference points used for station orientation and resection. In the presented case, the instrument positions were determined using six reference points, and the observations were performed in Face I only, without repeated observation series. This measurement strategy was sufficient for construction-site control purposes, but it does not allow a full separation of random and systematic compo-

Table 2: Baseline lengths and internal 3D baseline precision indicators for the example GNSS solution of point 30904

Reference station	Baseline length [m]	Internal 3D baseline precision indicator [m]	Solution type	Constellations
JED1	36686.39	0.0010	Phase Fixed	GPS, GLONASS, Galileo, BeiDou
KIEL	629.40	0.0005	Phase Fixed	GPS, GLONASS, Galileo, BeiDou
OSTC	51684.75	0.0011	Phase Fixed	GPS, GLONASS, Galileo, BeiDou
SKAR	26208.41	0.0010	Phase Fixed	GPS, GLONASS, Galileo, BeiDou
SZYD	40428.16	0.0011	Phase Fixed	GPS, GLONASS, Galileo, BeiDou

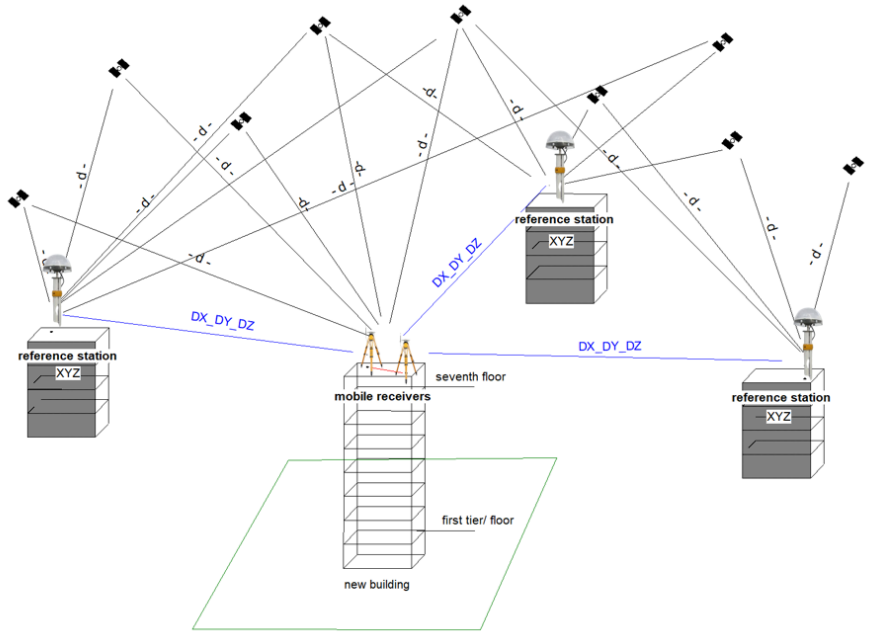


Figure 3: Static GNSS observation on a construction control point

Table 3: Free Station coordinate estimates and internal precision indicators [m]

Point	Storey	X [m]	Y [m]	H [m]	Sigma X [m]	Sigma Y [m]	Original FS ID
P1	ground storey	5638011.159	7475044.940	272.774	0.001	0.002	5500
P2	ground storey	5637941.083	7475032.860	271.821	0.001	0.001	5502
P3	upper storey	5638004.163	7475080.370	305.107	0.005	0.005	4501
P4	upper storey	5637975.502	7475070.109	305.114	0.003	0.004	4500

Table 4: Coordinate differences between the network-based static GNSS and Free Station solutions using unified point identifiers [m]

Point	Storey	GNSS X [m]	GNSS Y [m]	Free Station X [m]	Free Station Y [m]	dx [m]	dy [m]	d2D [m]
P1	ground storey	5638011.158	7475044.933	5638011.159	7475044.940	0.001	0.007	0.007
P2	ground storey	5637941.094	7475032.856	5637941.083	7475032.860	-0.011	0.004	0.012
P3	upper storey	5638004.163	7475080.375	5638004.163	7475080.370	0.000	-0.005	0.005
P4	upper storey	5637975.502	7475070.113	5637975.502	7475070.109	0.000	-0.004	0.004

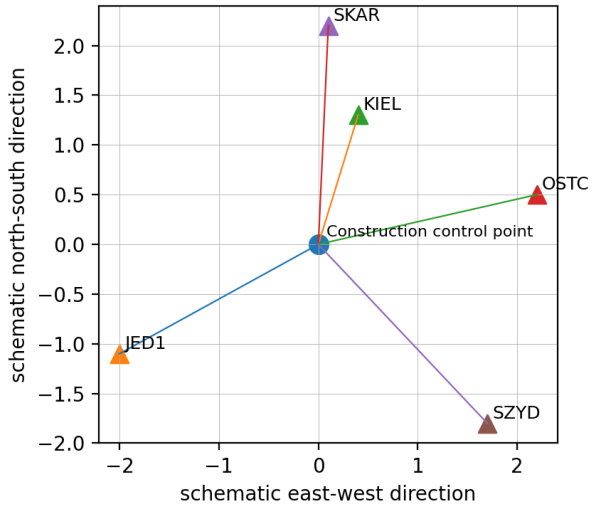


Figure 4: Schematic configuration of reference stations used in GNSS network-based post-processing. Axes show arbitrary dimensionless positions [-]; the diagram is not to scale. Baseline lengths are listed in Table 2.

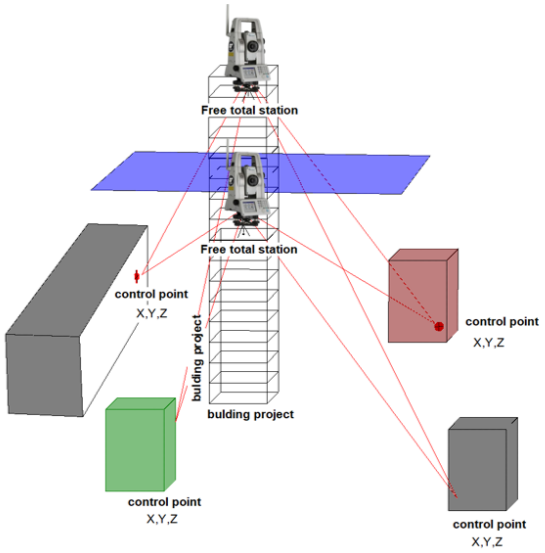


Figure 5: Application range of the Free Station method



Figure 6: Design visualisation of the investigated building (source: https://radiokielce.pl/1158070/)

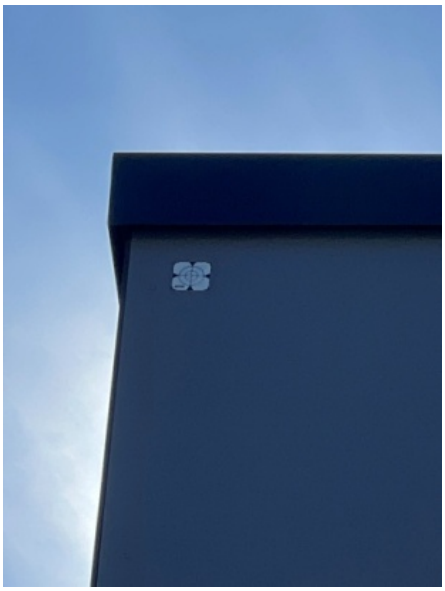


Figure 7: Construction control point stabilised as a distance-measuring foil



Figure 8: Static GNSS observation on a construction control point

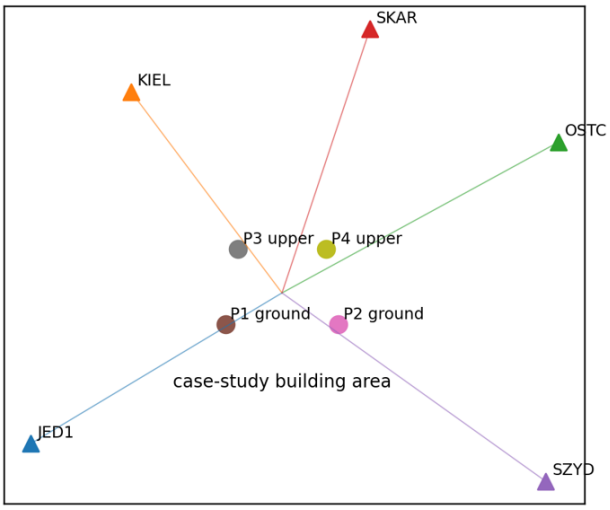


Figure 9: Location of the construction control network points and reference stations used for upper-storey observations; ground-storey points P1 and P2 are documented in Figure 11 and Table 4.

nents. Consequently, the discussion of vertical-angle effects and observation geometry should be understood as a plausible explanation rather than as a fully isolated error source.

The GNSS solution was obtained using one-hour static observations processed in a network-based post-processing strategy with five reference stations. The processing report confirmed a fixed phase solution and millimetre-level internal precision estimates. These parameters support the technical reliability of the GNSS solution in the analysed case. Nevertheless, internal GNSS precision estimates should not be interpreted as an independent assessment of external accuracy. They show the consistency of the GNSS network solution, but they do not replace validation against an independent reference system.

The results therefore support a complementary rather than competitive interpretation of the two methods. The Free Station method remains practical and efficient when reference points are visible, stable and well distributed around the construction site. Static GNSS, particularly in a network-based post-processing mode, may be useful when sky visibility is sufficient and when terrestrial observation geometry becomes less favourable. The choice of method should therefore depend on the construction stage, visibility conditions, required precision, accessibility of control points, and the possibility of independent checks.

From a practical engineering-surveying perspective, the results support the complementary use of terrestrial and satellite methods in construction control networks. This case study's limited number of investigated points and levels is discussed here as a limitation. A stronger methodological conclusion would require additional observations at several intermediate storeys, repeated measurement series, preferably Face I and Face II observations for the total station, and comparison with an independent higher-accuracy reference solution. These aspects are recommended for further research.

Additional literature on geodetic monitoring, reference-station stability, total-station applications, GNSS-based surveying and high-rise construction was retained as supporting background for the practical discussion of combined terrestrial and satellite measurement methods (da Silva et al., 2017; Cheng et al., 2023; Ali et al., 2016; Mrówczyńska and Sztubecki, 2021; Osada et al., 2023; Kowalska et al., 2025; Maciuk et al., 2025; Hayes et al., 2006; Jayamanne et al., 2025; Abdelbarr et al., 2025; Arabtec Engineering Services, 2018; Warchoł et al., 2024; Xu and Pan, 2025; Saba et al., 2025; Darrozes et al., 2016; Guo et al., 2008; EL-Hattab, 2013; Špiranec and Thurgood, 2025; Bagherbandi et al., 2023).

5 Conclusions

1. The presented study compares static GNSS and Free Station solutions for selected construction control points in a 10-storey residential building. It should be interpreted as a case study of coordinate agreement between two surveying approaches.

2. The coordinate differences between the GNSS and Free Station solutions were smaller on the upper storey than at the ground level. For the investigated dataset, the horizontal differences were approximately 7–12 mm at the ground level and approximately 4–5 mm at the upper storey.

3. Under the specific conditions of the analysed construction site, the agreement between the Free Station and static GNSS coordinate solutions was higher for the upper-storey points than for the ground-storey points.

4. The Free Station results are influenced by terrestrial observation geometry, visibility and distribution of reference points, instrument set-up and observation procedure. Because the observations were performed in Face I only and without repeated series, the related interpretation should be treated cautiously.

5. The GNSS results were obtained from one-hour static observations processed using Leica Spider Business Centre / SmartNet XPOS in a network-based post-processing strategy. The fixed phase solution and internal precision indicators confirm consistent processing for the analysed case.

6. For practical surveying of high-rise buildings, the results support the complementary use of both methods. Free Station measurements are effective when terrestrial control points are available and well distributed, whereas static GNSS may provide useful independent control where sky visibility and processing conditions are favourable.

7. Further validation should include more storeys, a larger number of control points, repeated total station observations in both faces and an independent reference solution of higher accuracy.

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GNSS processing report - summary
1. Results for the point
2. 30901
2.1. 30901 - 2025-09-03 16:44:36
2.1.1. JED1 - 30901
2.1.2. KIEL - 30901
2.1.3. OSTC - 30901
2.1.4. SKAR - 30901

Horizon angle: 10°
Frequency: L1, L2, L5, E5b, E5ab
Sampling frequency: 2 sek.
Satellite constellation: GPS, GLONASS, Galileo, BeiDou

Baseline summary 30901

Point no.	Ref. station	Baseline length	Coordinate accuracy. 3D [m]	ΔX m	ΔY m	ΔZ m	X m	Y m	Z m
30901							**3773910,5885**	**1421961,6746**	**4925153,8456**
	JED1	36658.6731 m	0.0004	0.0090	0.0080	0,0051	3773910.5795	1421961.6667	4925153.8405
	KIEL	638.0718 m 0.	0.0002	0.0014	-0,0008	0,0025	3773910.5871	1421961.6754	4925153.8431
	OSTC	51699.5421 m	0.0005	-0,0139	-0,0074	-0,0217	3773910.6024	1421961.6821	4925153.8673
	SKAR	26238.4892 m	0.0004	-0,0011	0.0012	-0,0068	3773910.5896	1421961.6734	4925153.8524
	SZYD	40412.0576 m	0.0005	-0,0079	0.0023	0,0026	3773910.5964	1421961.6724	4925153.8430

Point no.	Solution type	Measurements/ Baselines	Cartesian X WGS84	Cartesian Y WGS85	Cartesian Z WGS86	SD X	SD Y	SD Z
30901	Solution Phase Fixed	1./.4	**3773910.5885**	**1421961.6746**	**4925153.8457**	0.0028	0.0015	0.0034

Figure 10: Example of a network-based static GNSS coordinate computation report. The software label "3D coordinate accuracy" denotes an internal 3D precision indicator derived from component standard deviations, not an external accuracy assessment.

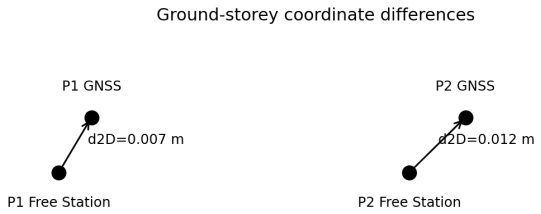


Figure 11: Coordinate differences between static GNSS and Free Station solutions for the ground-storey points P1-P2

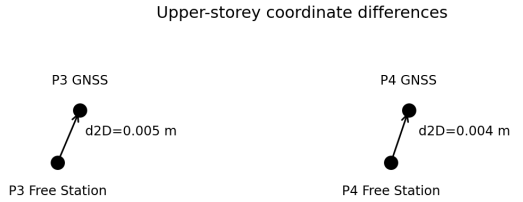


Figure 12: Coordinate differences between static GNSS and Free Station solutions for the upper-storey points P3-P4

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