

Experimental Evaluation of Low-Cost GNSS Receivers for Deformation Monitoring in High-rise Buildings

Jayamanne Mudalige Oshadee Jayamanne

`jayamanne.jayamanne@nottingham.ac.uk`

University of Nottingham

Panagiotis Psimoulis

University of Nottingham

John Owen

University of Nottingham

Nigel Penna

Ordnance Survey

Chenyu Xue

University of Nottingham

Research Article

Keywords: low-cost GNSS, structural health monitoring, deformation monitoring, high-rise buildings, displacement monitoring

Posted Date: October 21st, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10114301/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Title :**Experimental Evaluation of Low-Cost GNSS Receivers for Deformation Monitoring in High-rise Buildings****Authors:**

Jayamanne Mudalige Oshadee Jayamanne^{1*}, Panagiotis Psimoulis¹, John Owen¹, Nigel Penna², Chenyu Xue¹

Affiliations:

¹Faculty of Engineering, University of Nottingham, UK

²Ordnance Survey, UK

* Corresponding Author

Acknowledgements:

This study is funded by the EPSRC, UK through the CDT in Geospatial Systems under the grant reference EP/S023577/1

Conflict of Interests:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Corresponding Author Details:

J M O Jayamanne,
Nottingham geospatial Institute,
Faculty of Engineering,
University of Nottingham,
Nottingham,
NG7 2RD,
UK
+44 7585933162
Jayamanne.jayamanne@nottingham.ac.uk

Experimental Evaluation of Low-Cost GNSS Receivers for Deformation Monitoring in High-Rise Buildings

Abstract

Monitoring deformation of high-rise buildings can contribute to structural integrity, safety, and occupant comfort by providing insights into both quasi-static and dynamic structural responses. This study investigates the feasibility of using low-cost Global Navigation Satellite System (GNSS) technology for deformation monitoring of tall buildings. A series of controlled experimental studies, followed by a case study on 220m high building evaluate the accuracy of low-cost GNSS systems in comparison to high precise geodetic grade systems, under static, quasi-static, and dynamic moving conditions where centimeter to sub-centimeter level accuracy can be attained. The research focuses on the dual-frequency u-blox F9P receiver combined with three antenna configurations representing different performance classes: the Leica AS10 geodetic antenna, the Tallysman TWI 3972 antenna, and the u-blox ANN-MB-00 (patch) antenna. It is shown that the type of antenna and the incorporated satellite combinations have a considerable impact on the performance. Using low-cost receivers, an accuracy of better than 5mm was obtained for horizontal movements in quasi-static and dynamic conditions with up to 0.5 Hz oscillations. The vertical movement accuracy is better than 1cm for quasi-static and better than 2cm for dynamic conditions. It is demonstrated that consumer grade GNSS receivers and antennas possess the potential for delivering precise GNSS observations for a low-cost monitoring of high-rise structures

Keywords: low-cost GNSS, structural health monitoring, deformation monitoring, high-rise buildings, displacement monitoring

1 Introduction

Advances in engineering such as high strength materials, wind responsive façade systems and damping technologies for wind and seismic load have enabled the safe development of slender and tall structures (Lotfabadi 2014). However, high-rise structures experience a broad range of deformation resulting from their structural characteristics and loading conditions (Park et al. 2008; Lotfabadi 2014; Yuan 2021). The deformation monitoring of tall buildings is an important task (i) during the construction phase, to ensure the stability, the structural integrity and verticality of the building (Zhou et al. 2018), and (ii) during the operation of the tall building after the construction, to ensure the stability of the tall buildings during extreme wind and/or

seismic loading (Park et al. 2008). However, continuous deformation monitoring is not yet widely implemented as a routine practice in most tall buildings, with existing applications largely limited to research studies (Zhang et al. 2018a; Quesada-Olmo et al. 2018a). This study investigates the performance of low-cost receivers in combination with different antennas by considering the two principal categories of lateral movements in high-rise buildings: (i) Quasi-static motion and (ii) dynamic motion.

Quasi-static displacements are the slowly developed motions of tall buildings caused by solar radiation and/or by the slow varying fluctuations of wind. The scale of these movements can range from mm to cm level based on the structural load characteristics, but the slow development rate is their common characteristic. Field measurements reported by (Su et al. 2017) indicate that a ~230 m-high, 66-storey building exhibited mean horizontal displacements ranging from 12 to 61 mm per hour under a mean wind speed of 12.3 m/s. At the same time, the 600 m Canton Tower experienced wind-induced quasi-static top displacements of 71- 131 mm during Typhoon Usagi (Su et al. 2017). Dynamic vibrations of high-rise buildings arise from turbulent buffeting, vortex shedding and ground motion producing oscillatory response, when subjected to mean and seismic excitation (Chen et al. 2012; Azzara et al. 2021). Generally, the fundamental natural frequencies of tall buildings fall within 0.1–1.0 Hz, depending on parameters such as structural height, mass distribution, and lateral stiffness system. For example, full-scale monitoring of a 508 m super-tall building reported first-mode frequencies varying between 0.15–0.14 Hz, second-mode frequencies 0.41–0.45 Hz, and third-mode frequencies around 0.77–0.81 Hz, with frequency reductions up to 10% during strong earthquake excitation (Sun et al. 2022). Similarly, field measurements of a 108 m tall building during a typhoon excitation identified first translational and torsional frequencies of approximately 0.58–0.69 Hz. Reported dynamic displacement amplitudes are typically within the centimetre range, increasing to the meter level under severe wind or seismic events (Zhang et al. 2020; Hu et al. 2022; Chen et al. 2023).

Structural Health Monitoring (SHM) using Global Navigation Satellite Systems (GNSS) has been undertaken for over two decades (Moschas and Stiros 2011; Hamza et al. 2020a) on structures such as dams (He et al. 2004; Barzaghi et al. 2018; Xiao et al. 2019; Roque et al. 2021), buildings (Quesada-Olmo et al. 2018b; Zhang et al. 2018b) and long span bridges such as the Forth Road Bridge, UK and Tsing Ma Bridge, Hong Kong (Meng et al.; Psimoulis et al. 2008a; Moschas et al. 2013; Xue et al. 2022; Xue and Psimoulis 2023) with cm level accuracy and precision with geodetic grade GNSS setups. The constant advances in GNSS technology,

such as the operation of multiple GNSS satellite systems, high-sampling rate receivers and new methods for GNSS data processing, have substantially increased the accuracy and precision of GNSS measurements (Msaewe et al. 2017), and enhanced the performance of GNSS technology under challenging measuring and environmental conditions such as urban multipath conditions (Meng et al.; Msaewe et al. 2017). Traditional deformation monitoring techniques often rely on repeated field observations and significant data-processing effort, whereas GNSS-based systems facilitate continuous monitoring with minimal operator involvement.

A recent significant advance in GNSS technology is the development of low-cost, mass market, receivers which can provide sub-cm level accuracy with precise carrier phase observations and high-sampling rates (Cina and Piras 2015; Benoit et al. 2015; Biagi et al. 2016a; Odolinski and Teunissen 2017). These receivers provide significant advantages in terms of size, weight, and affordability, with costs typically 10–20 times lower than those of geodetic receivers. Low-cost single-frequency receivers have been examined against geodetic receivers in several previous studies. These studies have evaluated the accuracy and precision of single frequency receivers based on zero-baseline and/or short baseline experiments (Bellone et al. 2016; Caldera et al. 2016, 2022; Msaewe et al. 2017). According to the findings of these studies, single frequency GNSS receivers, can reach cm to sub-cm level precision over short baselines (up to 10 km) and a higher precision can be obtained by adopting a geodetic or choke-ring GNSS antenna (Xue et al. 2022; Xue and Psimoulis 2023). Furthermore, the accuracy of single-frequency receivers has been assessed in determining structural motion of civil engineering structures while developing approaches to limit the effect of error sources (e.g. multipath; (Xue et al. 2022, 2023)). These receivers have been evaluated for monitoring dams and bridges and have also been assessed within networks of sensors (Meng et al.; Moschas and Stiros 2011; Biagi et al. 2016b; Hamza et al. 2020b; Xue and Psimoulis 2023; Xue et al. 2023).

The achievable observation accuracy and precision of low-cost receivers have been improved by their recently developed capacity to track dual frequency L1/L2 or L1/L5 GNSS signals (Cina and Piras 2015) and thus potentially broadening their field of application. However, there is only a limited number of research assessing the noise levels of dual frequency receivers (Hamza et al. 2020b, 2023) which showed that sub-cm level accuracy can be reached based on rigorous observation and processing techniques. Such studies mostly focused on bridges and other rigid structures but not yet tall buildings, which exhibit different structural behaviour and, multipath conditions. Therefore, this study aims to evaluate the capability of dual-frequency low-cost GNSS receivers to monitor the slow/quasi-static and dynamic movements of high-

rise buildings. A low-cost GNSS receiver with various grades of antenna (from low-cost to geodetic grade) was used and investigated their performance through controlled experiments in which known static observations, quasi- static and dynamic motions were introduced simulating the response characteristics of tall buildings. The second phase of the study was to use the low-cost GNSS setups on a real application of tall-building monitoring to assess their performance and reliability in urban environmental and operating conditions.

Thus, the study involves a holistic investigation of low-cost GNSS receivers for tall-building monitoring based on dual-frequency low-cost GNSS receivers and three types of antennas including geodetic, low-cost with modelled phase centre, and low-cost without a modelled phase centre, which has not been previously investigated for this type of assessment. The study comprehensively investigates the significantly different monitoring challenges of high-rise buildings compared to other SHM applications, due to low-amplitude dynamic displacements, long-period oscillatory behaviour, vertical flexibility and severe urban multipath environments.

2 Methodology of the experiments

The experiments were designed to investigate the effects of (i) antenna selection and (ii) multi-GNSS constellation combinations on the positioning performance of low-cost GNSS receivers for monitoring motions ranging from mm to cm level as experienced by tall buildings (Su et al. 2017). The dual-frequency (L1/L2) low-cost GNSS receiver was assessed with three grades of antennas: (i) geodetic-grade antenna (Leica AS10), (ii) low-cost with a modelled phase centre calibration (Tallysman TWI 3972) and (iii) low-cost with no model of the phase centre calibration (u-box patch). Also, different multi-GNSS solutions were assessed to examine the impact of the different satellite constellations (i.e. GPS, Galileo, GLONASS, BeiDou) on the performance of low-cost receivers (Jayamanne et al. 2025). The experiments include a static observation test to analyse the performance of GNSS setups in a non- moving environment followed by slow and dynamic movement tests replicating the quasi-static and dynamic motions of tall buildings. During static observation, the coordinate solution accuracy of the low-cost GNSS receivers was obtained by comparing against the reference coordinates determined based on 15-days period of multi-GNSS measurements post processed against multiple base stations and also with positions obtained with geodetic grade GNSS receivers (Psimoulis et al. 2008b; Psimoulis and Stiros 2013; Peppas et al. 2017). For the slow and dynamic motion experiments, measurements from a Leica TS30 Robotic Total Station (RTS)

were used as reference data which have been deemed by (Peppas et al. 2017) to have mm-level accuracy.

3 Static experiment

3.1 Experimental design

The primary objective of this experiment was to investigate the performance of dual-frequency low-cost GNSS receivers and assess the influence of low-cost antennas on positioning accuracy, with and without modelled phase centre orientation during GNSS friendly observing conditions and no antenna movement. Thus, it will provide a baseline for evaluating the low-cost GNSS receivers during slow and dynamic movements. The test was conducted on the roof top laboratory of the Nottingham Geospatial Institute (NGI) building in Nottingham, UK, where a continuously operating base station (Leica GR10 -AR25) formed a 17 m long baseline with the rover station. Three setups were examined where one type of antenna was tested individually: (i) Leica AS10 antenna (geodetic), (ii) Tallysman TWI 3972 antenna (low-cost) and (iii) u-blox patch antenna (low-cost). Fig. 1 illustrates the experimental setup of the test. Each rover antenna was individually connected to a geodetic receiver (Leica GS10) and a low-cost receiver (u-blox F9P) through a signal splitter, and 1 Hz L1 and L2 GNSS data were recorded by each receiver for 24 hours. The Leica GS10 receiver recorded the data internally, while the u-blox receiver was connected to a Raspberry Pi device for recording u-blox GNSS data. In order to undertake comparisons with the same satellite geometry for both GPS and Galileo, the data collection was repeated ten sidereal days later (one Galileo repeat period and 10 GPS repeat periods).

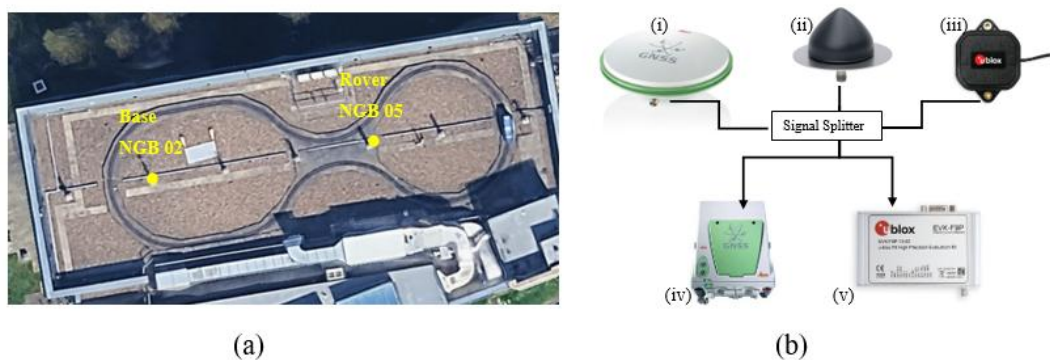


Fig. 1: (a)-Satellite view of the base and rover stations on the NGI rooftop. (b) Experimental design: (i) Leica AS10, (ii) Tallysman TWI 3972 and (iii) u-blox patch antennas connected via a signal splitter to (iv) Leica GS10 geodetic receiver and (v) U-blox F9P low-cost receiver

3.2 Data processing

The GNSS data were processed using RTKLIB *demo5 b34k* (Everett et al. 2022), in post-processed kinematic mode (PPK) with coordinates estimated at 1 Hz over the 24- hour batches. Due to the relatively free multipath environment, a 7-degree elevation mask was applied and because the baseline length was only 17 m broadcast ephemeris data were used for processing.

Three GNSS data solutions were produced for each experiment using; (i) GPS satellites only, (ii) GPS and Galileo satellites only , and (iii) GPS, Galileo and GLONASS satellites. For solutions involving GLONASS signals, receiver- specific inter-system frequency bias corrections were applied(Wanninger 2011). BeiDou satellites were not included in the solutions for this test, as the base station did not record BeiDou data during the observation period.

3.3 Time series analysis

From the estimated coordinates of each solution, the static GNSS reference coordinates were removed, leaving coordinate residuals against which the scatter and bias of the low-cost solutions could be assessed. In Fig. 2 Easting residuals are shown for the Leica and u-blox receivers for all three antennas for GPS, Galileo and GLONASS satellite solution. The AS10 geodetic antenna provided the best noise performance for both receiver types, with the residual time series of the geodetic and low-cost receivers exhibiting standard deviations of 1.9 mm and 2.0 mm respectively, as listed in Table 1. However, the residuals with low-cost GNSS antennas are only slightly larger, all within the range 2.4- 3.0 mm for both the Tallysman and patch antennas for both the geodetic and low-cost receivers.

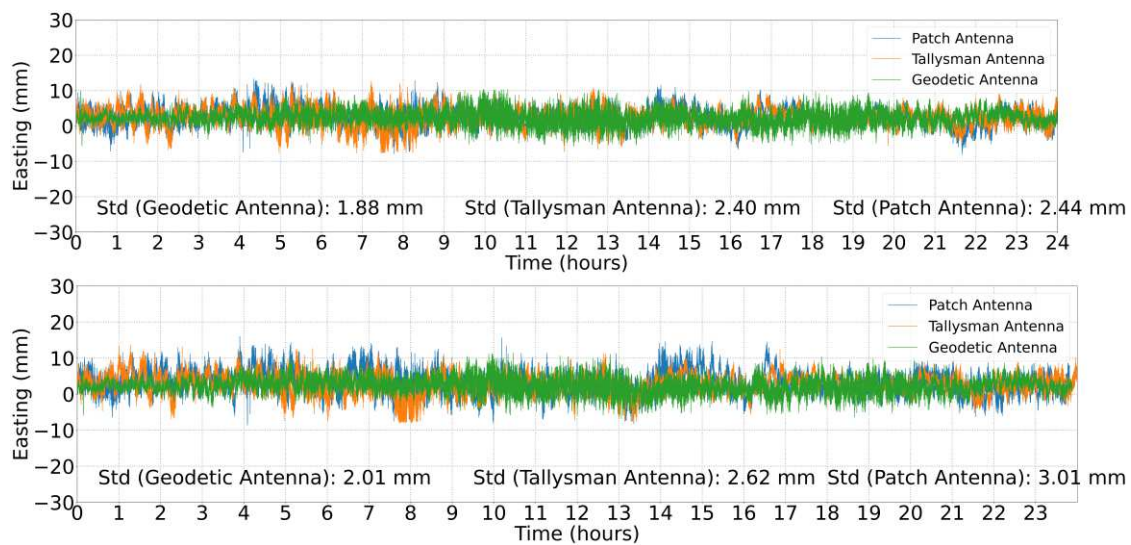


Fig. 2: Static experiment-time series of easting residuals (observed - known static reference) from Leica GS10 receiver (top) and u-blox F9P low-cost receiver (bottom) for a combined GPS, Galileo and GLONASS solution.

Table 1: Static Experiment -casting standard deviation from different satellite configurations for Leica AS10 receiver and u-blox low-cost receiver

	Standard Deviation (mm)								
	Geodetic Antenna			Tallysman Antenna			Patch Antenna		
	GPS	GPS/ GAL	GPS/GAL/ GLO	GPS	GPS/ GAL	GPS/GAL/ GLO	GPS	GPS/ GAL	GPS/GAL/ GLO
Geodetic	2.4	2.2	1.8	3.4	2.8	2.4	3.2	2.8	2.4
Low-Cost	2.6	2.3	2.0	3.8	2.9	2.6	3.7	3.7	3.0

Table 1 depicts the standard deviations of residual GNSS time-series for different satellite combinations. The results demonstrate that the combination of the geodetic antenna with the geodetic receiver achieved the highest precision ranging between 1.8-2.4 mm, for all three satellite combinations, while the combination of low-cost receiver and geodetic antenna achieves a comparable level of precision (i.e. range 2.0-2.6 mm). Solutions for the Tallysman antenna with both Leica and u-blox receivers are slightly less precise, with the standard deviation in the range 2.4-3.4 mm and 2.6-3.8 mm, respectively. The least precise observations were obtained using patch antenna, achieving standard deviation of 2.4-3.2 mm and 3.0-3.7 mm, for the geodetic and u-blox receivers, respectively.

In this experiment, the patch antenna consistently demonstrated the lowest precision with the low-cost receiver, irrespective of the satellite constellations used. Patch antennas, widely utilised in geospatial applications such as mobile GIS and precision agriculture, are typically more vulnerable to multipath interference and exhibit reduced signal sensitivity relative to survey-grade GNSS antennas, as also shown by the findings of (Hamza et al. 2020b, 2023; Xue et al. 2022). Conversely, the Tallysman antenna, although a low-cost choice, exhibited performance similar to that of the survey-grade antenna.

It can be concluded that, low-cost dual frequency GNSS receivers can also achieve a similar level of precision to the geodetic receivers, and the negative impact of the low-cost antennas can be limited by applying a multi-GNSS solution. The option of using a low-cost antenna such as the Tallysman, but with modelled phase centre orientation enhances the precision of the low-cost GNSS receiver compared to those without a modelled phase centre. The use of a geodetic antenna will further enhance the performance, as the precision difference was limited to less than 1 mm between low-cost and geodetic receivers.

A Power Spectral Density (PSD) analysis was undertaken to provide an assessment of the signal quality. PSDs were estimated using Welch method with a *Hanning* window of 2048

points per segment and an overlap of 1024 points as per (Xie et al. 2013). The estimated PSD values are shown in Fig. 3 and indicate that for the low-cost receiver, the geodetic antenna shows a consistently lower noise across low frequencies than the patch and Tallysman antennas. However, from the PSD results of the low-cost antenna solutions, the Tallysman antenna shows a lower noise during both coloured and white noise regions of the power spectrum compared to the patch antenna. This suggests that more precise observations can be attributed to the hardware quality and lower susceptibility to multipath interference of the Tallysman antenna.

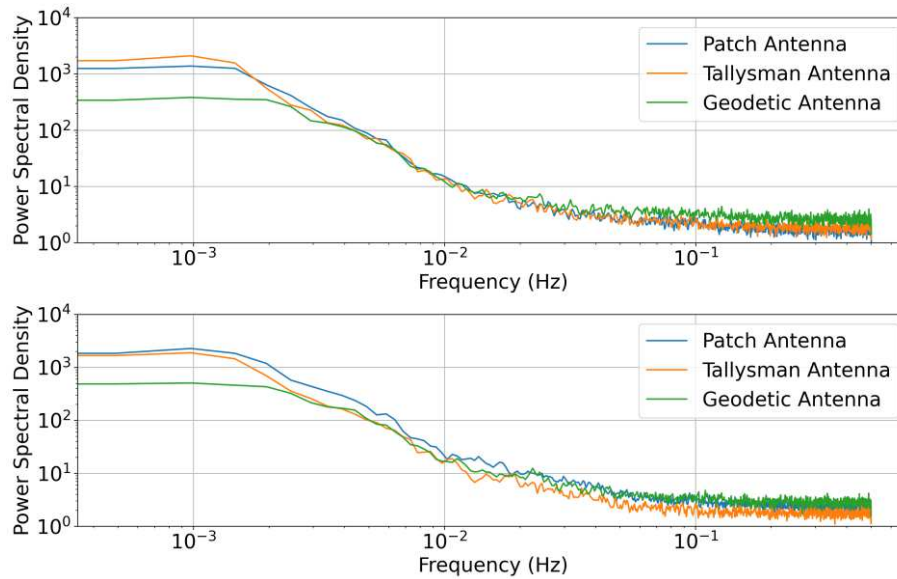


Fig. 3: Static experiment- PSD comparison of easting residuals derived from the GPS, Galileo, GLONASS solution. Results are shown for the Leica GS10 receiver (top) and the u-blox F9P receiver (bottom) equipped with geodetic, patch, and Tallysman antennas.

The Northing and Vertical components of the time series demonstrated a similar assessment. The results for the Northing and Vertical components are supplied in the supplementary materials.

4 Quasi-static experiment

4.1 Experimental design

A quasi-static experiment was undertaken on the rooftop laboratory of the NGI building, in which controlled displacements were introduced to the GNSS antenna locations in order to simulate the slowly developed motion of tall buildings, caused by the wind and/or thermally induced deformation (Nickitopoulou et al. 2006; Su et al. 2017). For the quasi-static experiment, 1 cm horizontal (E-W) and vertical displacements were manually applied every hour during continuous GNSS observations. An experimental device which was designed to introduce

horizontal and vertical axial displacement was used for this experiment. The displacements were introduced manually by controlling and adjusting the device position through a graduated scale.

Fig. 4 illustrates the experimental setup. Three antennas; (i) Leica AS10 ,(ii) Tallysman TWI 3972 and (iii) u-blox patch were set up on top of the experimental device forming a 14 m baseline with a separate Leica GS10-AS10 base station. The rover Leica AS10 was connected via a splitter to a u-blox F9P L1/L2 receiver and a Leica GS10 receiver, while the Tallysman and the patch antennas were connected directly to an individual u-blox receiver. All the GNSS receivers recorded L1 and L2 GPS, Galileo, GLONASS and BeiDou code and phase data at 1Hz for 6 hours. Mounted on top of the Leica GS10 antenna was a 360-prism which was tracked by a Leica TS30 RTS which determined the reference value of simulated displacement.



Fig. 4: Rooftop test configuration used for the quasi-static experiment at the NGI, including a Leica 360 prism, a Leica AS10 geodetic antenna connected to both Leica GS10 and u-blox F9P receivers, and Tallysman TWI 3972 and patch antennas paired with separate u-blox F9P receivers.

4.2 Data processing and GNSS time series analysis

The GNSS data were processed using RTKLIB *demo5 b34k* with the same settings (except as hereafter described) as for the static experiment. For each GNSS receiver, there were solutions; (i) GPS only, (ii) GPS and Galileo, and (iii) GPS, Galileo and BeiDou. The main difference with respect to the static experiment is that BeiDou constellation was included in the analysis. GLONASS satellites were removed from the solutions, as the GLONASS data suffered data loss and cycle slips even after the IFB corrections were applied.

From each GNSS solution three GNSS time-series of Easting, Northing and Up-components were obtained, which shows the relative movement of the receivers from their initial position. The experimental device was levelled, and the horizontal axis of the experimental device was aligned with the East-West direction. Hence the Up and Easting components of the GNSS time-series expressed the total vertical and total horizontal displacement, respectively.

The relative movements observed by each antenna- receiver setup are shown in Fig. 5. Table 2 shows the absolute errors in E-W movement from low-cost GNSS receivers against the RTS observations for the GPS, Galileo and BeiDou combination along with respective standard deviations of the observations, computed by summing the variances of the two intervals. The patch antenna consistently exhibited the worst positional accuracy across all examined movement scenarios with errors ranging from 2.3- 5.1 mm. The drop in performance could also be attributed to interference from the geodetic antenna, which was positioned close to the patch antenna which may have disrupted the GNSS signals it received (Kubo et al. 2017; Xue et al. 2022). In contrast, the Tallysman antenna exhibited comparable performance in the initial three movements with accuracies within ± 2 mm even when positioned in proximity (< 20 cm) to the geodetic antenna. The notable increase in errors observed in the final movement scenario is attributable to the unexpected reduction of satellite geometry during the measurement period, which also exhibited high DOP values (> 3).

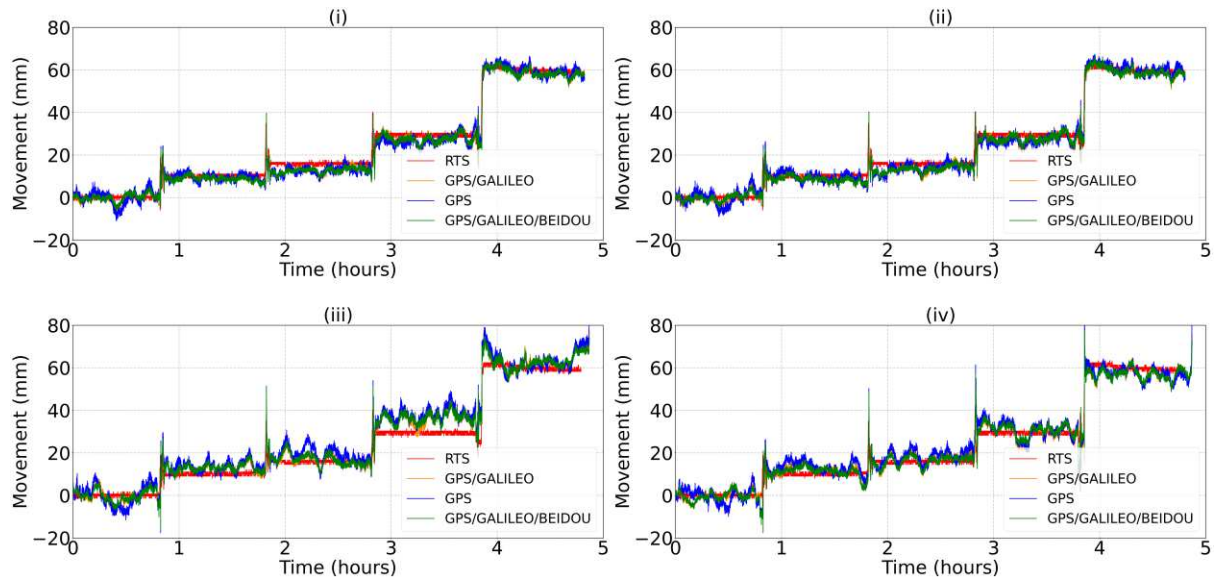


Fig. 5: Quasi-static experiment- horizontal displacement time series derived from four GNSS configurations (i) Leica GS10–AS10, (ii) u-blox F9P–AS10, (iii) u-blox F9P–Patch, and (iv) u-blox F9P–Tallysman

Table 2: Quasi-static experiment absolute horizontal movement errors (mm) with respect to RTS reference data for GPS, Galileo, BeiDou combination for different receiver- antenna setups

Movement Amplitude (mm)	Horizontal Displacement Error (mm)			
	Leica GS10- Leica AS10	U-blox F9P - Leica AS10	U-blox F9P – Patch	U-blox F9P - Tallysman
5.74	1.85 ± 1.53	0.70 ± 1.94	2.33 ± 3.17	0.90 ± 2.67
10.11	1.05 ± 2.07	1.42 ± 2.14	3.43 ± 3.12	1.87 ± 2.68
13.51	0.89 ± 2.19	0.60 ± 2.38	6.23 ± 3.71	0.28 ± 3.43
30.46	0.78 ± 2.65	0.70 ± 2.66	5.05 ± 3.67	4.00 ± 3.60

As shown in Fig. 6, the vertical component noise levels are substantially greater than those of the horizontal components. However, a similar pattern was observed in the performance with the geodetic setup which showed the highest precision and patch antenna which showed the lowest precision. As listed in Table 3, the full geodetic setup showed an accuracy ranging from 0.3-1.5 mm against RTS. The accuracy is slightly decreased (0.9- 3.6 mm) when the geodetic antenna was coupled with a low-cost receiver. Among the two fully low-cost setups the errors of the Tallysman antenna against the RTS ranged from 5.9 mm to 12.1 mm. The patch antenna showed elevated noise levels throughout the observation period as shown in Table 3.

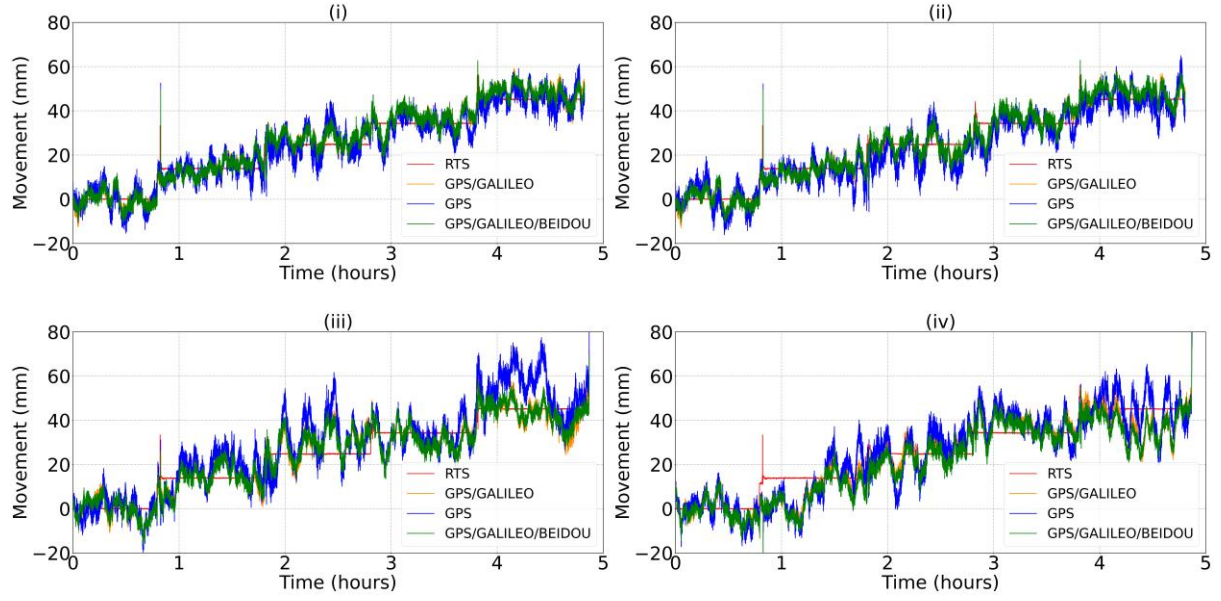


Fig. 6: Quasi-static experiment- vertical displacement time series derived from four GNSS configurations (i) Leica GS10-AS10, (ii) u-blox F9P-AS10, (iii) u-blox F9P-Patch, and (iv) u-blox F9P-Tallysman

Table 3: Quasi-static experiment absolute vertical displacement errors (mm) with respect to RTS reference data for GPS, Galileo, BeiDou combination for different receiver- antenna setups

Movement Amplitude (mm)	Vertical Displacement Error (mm)			
	Leica GS10- Leica AS10	U-blox F9P - Leica AS10	U-blox F9P – Patch	U-blox F9P - Tallysman
13.88	0.98 ± 5.24	0.90 ± 5.25	2.03 ± 9.17	5.92 ± 6.32
10.89	1.56 ± 5.04	0.92 ± 5.73	3.35 ± 9.31	4.61 ± 7.13
9.51	0.64 ± 5.09	3.61 ± 5.98	7.95 ± 6.58	4.63 ± 7.47
10.87	0.36 ± 5.19	0.92 ± 5.35	0.63 ± 7.36	12.06 ± 7.13

PSDs of the GNSS data were calculated using the Welch method for a Hanning window of 2096 points per segment and an overlap of 1024 points, similar to the static experiment. The PSD curves for E-W movement for different satellite combinations are shown in Fig. 7. of the two low-cost set ups, Tallysman and u-blox F9P combination shows a reduced noise level in both coloured and white noise regions compared with the patch antenna and u-blox combination. This further demonstrated that a low-cost GNSS receiver with an appropriate antenna is capable of detecting and tracking slow and gradually occurring horizontal and vertical displacements of up to 1cm.

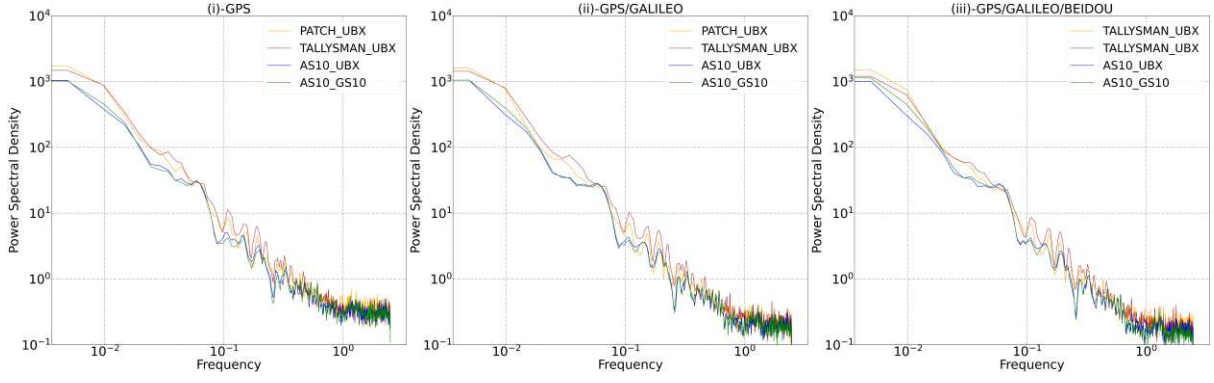


Fig. 7: Quasi-static experiment: PSD values of the GNSS observations obtained from Leica AS10, Tallysman and Patch antennas with low-cost receiver. Subplots: (i) GPS (ii) GPS, Galileo (iii) GPS, Galileo and Beidou

5 Experiment of dynamic displacement

The performance analysis during dynamic displacement was conducted through controlled vibrations at a selected frequency range. The test was also conducted at the Nottingham Geospatial Institute using an APS 113 air-bearing electrodynamic shaker, which can provide a maximum force of 133 N and a peak-to-peak displacement capacity of 158 mm (Häberling et al. 2015; Patnana and Rai 2022). Four frequencies of oscillations, 0.1 Hz, 0.25 Hz, 0.5 Hz and 1 Hz, were considered in the dynamic tests, which are typical of the long period oscillations of tall structures due to wind load (Kijewski-Correa and Pirnia 2007). Excitations were produced using a signal generator connected to the shaker, to generate three target displacement amplitudes: (i) <1 cm (ii) 2-3 cm, and (iii) 6-7 cm. Similar to previous experiments, the performance of a dual-frequency u-blox F9P (L1/L2) receiver was assessed using Leica AS10 and Tallysman TWI 3972 antennas. The patch antenna was not included in this test based on the lower precision recorded in the previous experiments. 5 Hz dual frequency L1/L2 data were recorded during the experiment. RTS observations were again used as reference data.

As shown in the Fig. 8, the results from both antennas follow a similar trend. At 0.1 Hz the Leica AS10 (geodetic) antenna closely matches the RTS data while the Tallysman antenna exhibits cycle slips most likely due to sudden multipath interference. When the excitation frequency increases, both antennas exhibit significant deviations from the RTS data; however, both antennas maintain a consistent waveform. To eliminate low-frequency errors, a Chebyshev Type I high-pass filter was introduced to the data with a 0.1 Hz cut off frequency. Fig. 9 shows the filtered result for amplitude level <10 mm for different excitation frequencies.

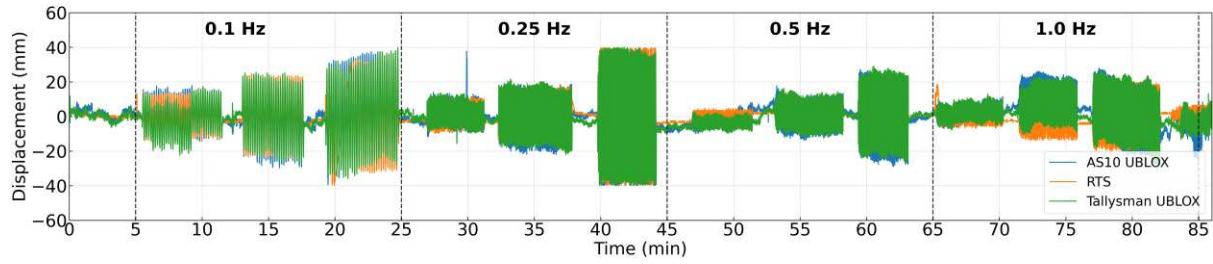


Fig. 8: Dynamic movement experiment: displacement time series for GNSS setups Tallysman L1/L2- u-blox F9P, Leica AS10- u-blox F9P and RTS for 0.1 Hz, 0.25 Hz, 0.5 Hz and 1 Hz shaker oscillations.

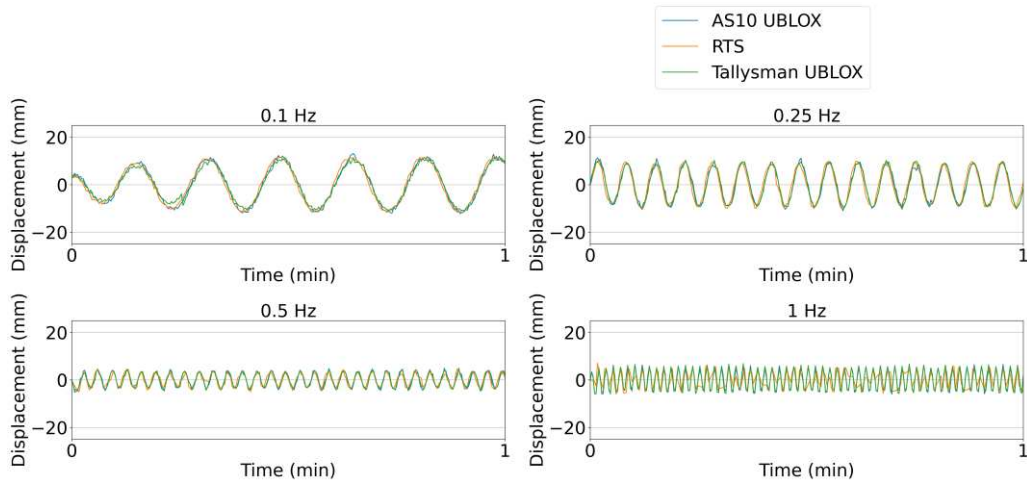


Fig. 9: Dynamic experiment: Filtered time series for oscillations for amplitude range <10mm

The average peak-peak error of the GNSS data against RTS are shown in Fig. 10 for amplitudes <10mm, indicating a close performance between the two antennas with the mean peak to peak errors for Tallysman antenna ranging from 0.0- 5.0 mm and the AS10 antenna ranges from 0 to 4.8 mm.

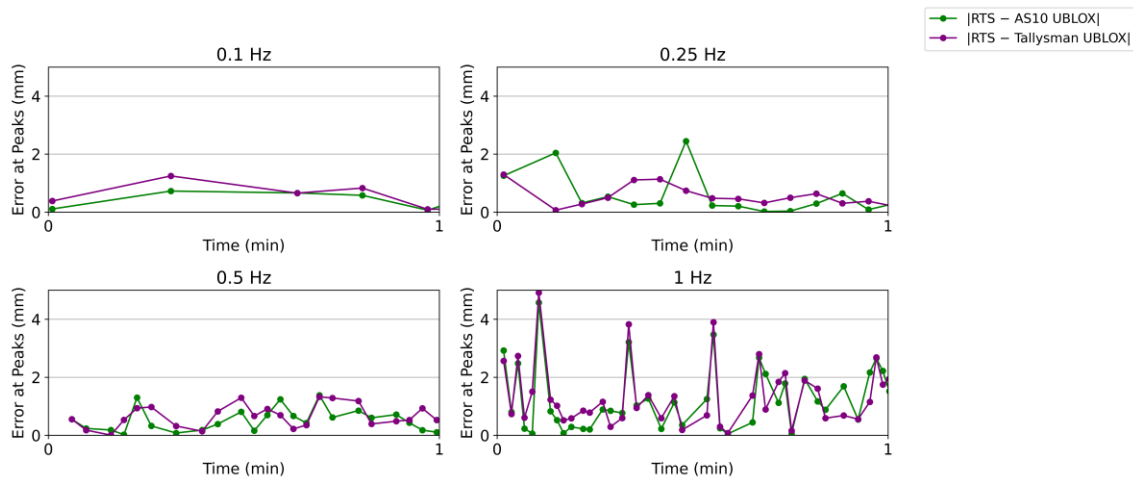


Fig. 10: Dynamic movement experiment: peak to peak error against RTS measurements for 0.1 Hz, 0.25 Hz, 0.5 Hz and 1.0 Hz excitations for amplitudes <10 mm

Fig. 11 presents the PSD results for all oscillations computed using the Welch method with a 2096 points per segment and 1024-point overlap. Between these two low-cost receiver configurations, the Tallysman low-cost antenna consistently shows slightly higher PSD values at low frequencies compared to the geodetic antenna, particularly below 0.3 Hz. Additionally, while both configurations converge at higher frequencies, the AS10 signal exhibits fewer narrowband peaks, implying better noise stability in the higher frequency domain.

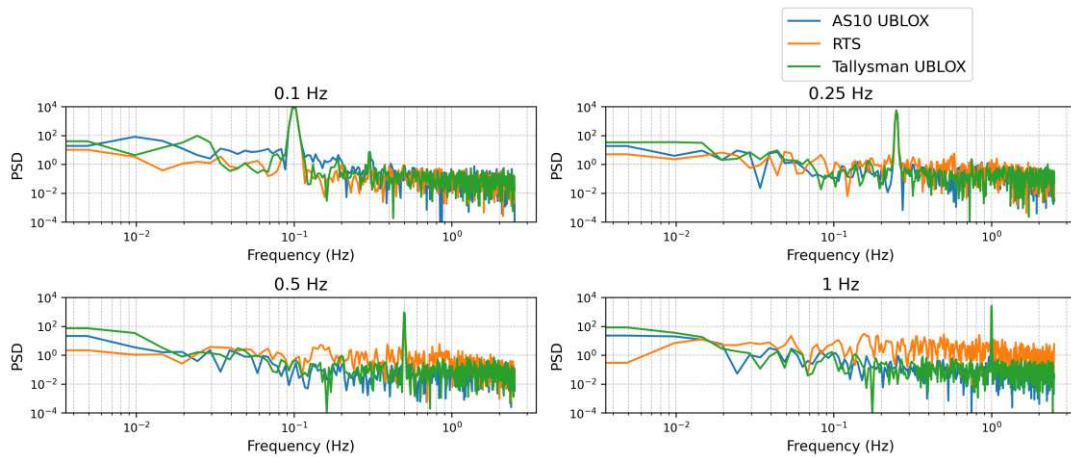


Fig. 11: Dynamic movement experiment: PSDs for 0.1 Hz, 0.25 Hz, 0.5 Hz and 1.0 Hz excitations for amplitudes <10 mm for u-blox F9P receiver with Leica AS10 and Tallysman antennas

6 Case study: short-term monitoring of a 220 m building

A preliminary case study was conducted on a 220m tall building with a concrete-steel composite structure in London, UK. The primary objective of this experiment was to assess the performance of dual frequency low-cost GNSS receivers and antennas under real-world operational conditions, with particular emphasis on assessing data quality in environments where error sources such as multipath cannot be completely eliminated. On the roof of the tall building, three GNSS stations were installed; (i) a Leica AS10 antenna connected to a Leica GS10 receiver and a u-blox F9P dual frequency (L1/L2) GNSS receiver through a signal splitter, (ii) a Tallysman TWI 3972 antenna connected with a u-blox F9P GNSS receiver, and (iii) a u-blox patch antenna connected with a u-blox F9P GNSS receiver (Fig. 12). Hence, effectively four GNSS rover stations were recording 1 Hz dual frequency L1/L2 data. The rover stations were located at three of the four corners of the concrete core of the tall building, in order to minimise the impact of obstructions and reflections from surrounding metallic and steel surfaces thus, to reduce GNSS multipath effects [47].

1 Hz dual frequency code and phase data from the 5 km distant Stratford Ordnance Survey ‘OS Net’ GNSS receiver were used as a reference station. The data were post-processed as a PPK solution using the RTKLIB software and same configurations as used for the laboratory static, quasi-static and dynamic experiments. Observations from the fully geodetic (Leica AS10/GS10) station was used as the reference solution for the experiment.

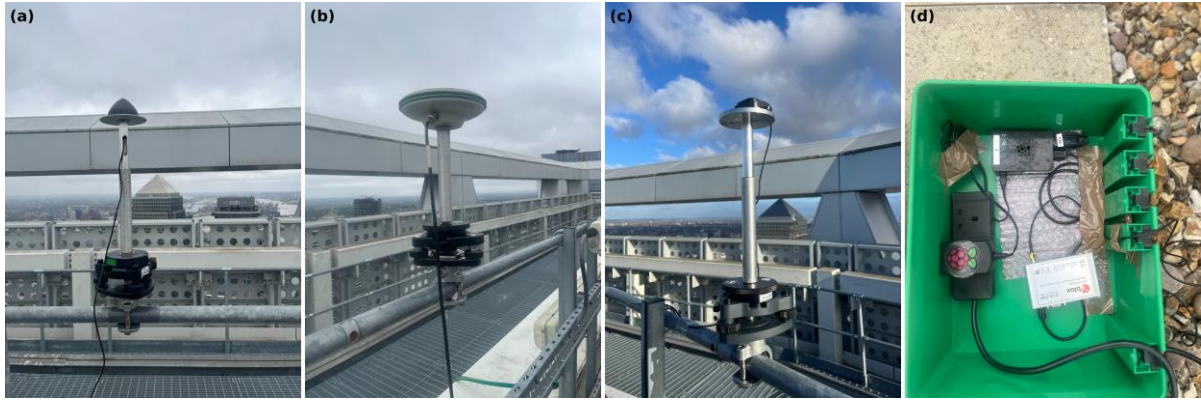


Fig 12: Tall building case study: the three GNSS stations on the roof of the tall building: (a) Tallysman, (b) Leica AS10, (c) u-blox ANN-MB-00 antennas placed on the handrail and (d) u-blox F9P receiver and data logger placed in waterproof box.

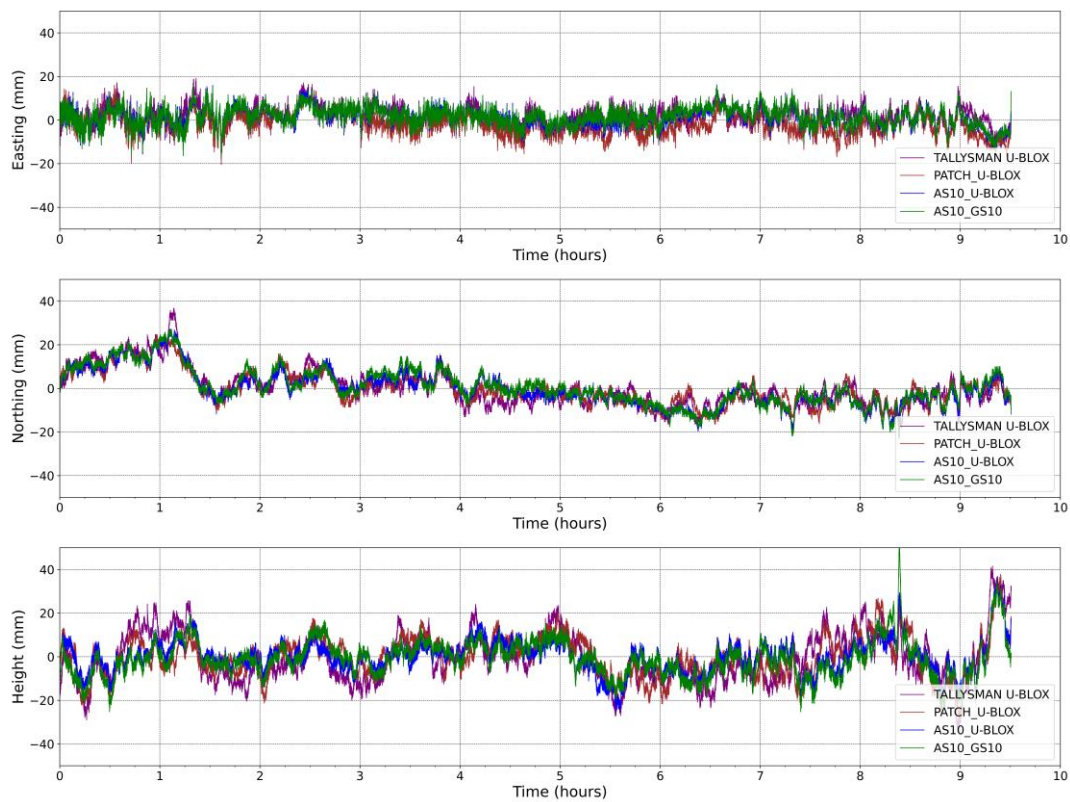


Fig. 13: Tall building case study: the easting, northing and up movements as recorded by GNSS setups; (i) Leica AS10-GS10, (ii) Leica AS10-u-blox F9P, (iii) Tallysman TWI-u-blox F9P, (iv) u-blox patch-u-blox F9, for a combined GPS, Galileo and Beidou multi-GNSS solution.

Table 4: RMSE of easting, northing and up components against geodetic (Leica AS10/GS10) setup for GPS, Galileo and Beidou multi-GNSS solution

	RMSE (mm)		
	Leica AS10-u-blox F9P	Tallysman-u-blox F9P	Patch-u-blox F9P
E	2.16	3.13	4.17
N	2.05	3.55	4.21
H	3.85	6.42	8.86

A 10-hour GNSS dataset was used to assess the performance of the different GNSS antenna-receiver set ups and the effects of the antenna selection on the low-cost GNSS receiver accuracy. Fig. 13 presents the Easting, Northing and Up components of the GNSS solutions and Table 4 lists the root mean square error (RMSE) of the low-cost u-blox time-series for the various antenna settings with respect to the geodetic setup. It is seen that again the low-cost GNSS receiver and the geodetic receiver show similar performance when they are connected to a geodetic antenna with RMSEs of the AS10 (geodetic) antenna and low-cost receiver ranging from 2.1 mm- 3.9 mm, commensurate with the results from the laboratory experiments. The u-blox receiver connected with the patch antenna showed the highest deviation from the reference setup, as the respective RMSE has the larger values (4.2 mm- 8.9 mm). U-blox receiver with Tallysman antenna achieved a performance comparable to the geodetic setup in the horizontal position components, as the RMSE of Easting and Northing has low values (3.15 and 3.55 mm). However, the up component has slightly reduced precision compared to those of the horizontal components as indicated by the higher RMSE (6.42 mm). Also, small variations of the GNSS solutions between the three GNSS stations should be expected due to slightly different multipath environment, even though the three GNSS stations are closely located (within 10-15 m distance).

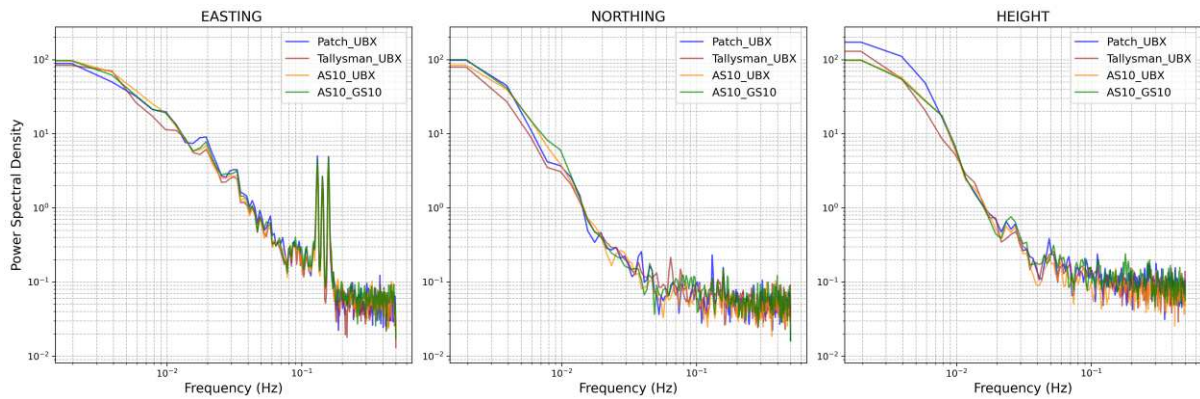


Fig. 14: PSD of Easting, Northing and Up recorded by recorded by GNSS setups; (i) Leica AS10-GS10, (ii) Leica AS10-u-blox F9P, (iii) Tallysman TWI-u-blox F9P, (iv) u-blox Patch-u-blox F9P, for a GPS, Galileo and Beidou multi-GNSS solution.

The PSDs were calculated using the Welch method for a *Hanning* window of 2096 points per segment with 1024 points overlap for E, N and Up positioning data recorded by different GNSS setups. As shown in Fig. 14, three distinct frequencies; 0.130 Hz, 0.142 Hz and 0.158 Hz were identified in the Easting component. These frequencies are consistent among all the geodetic and low-cost GNSS setups and across all the different time periods that were investigated they correspond to the natural frequencies of the observed tall building as confirmed by the design of the structure.

7 Conclusions

The main aim of this study was to establish baseline performance under controlled experiments and short-term observations for dual frequency (L1/L2) low-cost GNSS receivers for the context of SHM in high-rise buildings. Thus, in this study, the performance of consumer grade low-cost GNSS receivers and antennas were assessed during static, quasi-static and dynamic moving conditions. The experiments were designed to simulate the quasi-static movements and slow and long-term vibrations that are most common in tall structures due to thermal radiation, wind load and other environmental forces (Yi et al. 2013; Quesada-Olmo et al. 2018b; Yuan 2021). The results demonstrate that low-cost GNSS receivers can be incorporated in identifying the quasi-static displacements of tall buildings ranging from cm to m level as well as for the dynamic vibrations ranging from 0.1 Hz to 1 Hz.

The experiments were followed by a short-term case study on a residential high-rise building of 220m height. It can be concluded that the u-blox F9P L1/L2 GNSS receiver can reach a comparable precision to a geodetic grade GNSS receiver and can achieve a sub-centimetre accuracy when appropriate observation and processing strategies are applied, such as measures to mitigate multipath and the use of multi-GNSS solutions. For horizontal components, an accuracy of better than 5mm can be obtained when coupled with a geodetic antenna or a low-cost antenna with defined phase centre models. The vertical component exhibited higher noise levels than the horizontal components; however, the observed noise remained below 2 cm, which is consistent with findings reported in previous low-cost GNSS-based SHM studies (Hamza et al. 2020b, a; Xue et al. 2022; Xue and Psimoulis 2023). Furthermore, the building case study demonstrated the practical applicability of low-cost GNSS systems, even under real-world conditions where atmospheric effects and multipath errors could not be fully mitigated.

Overall, this study demonstrates that the low-cost GNSS technology is a viable alternative to the traditional GNSS systems for monitoring high-rise buildings. These findings highlight the potential for significantly reducing monitoring costs without compromising data quality.

References

- Azzara RM, Girardi M, Iafolla V, et al (2021) Ambient Vibrations of Age-old Masonry Towers: Results of Long-term Dynamic Monitoring in the Historic Centre of Lucca. *International Journal of Architectural Heritage* 15:5–21.
<https://doi.org/10.1080/15583058.2019.1695155>
- Barzaghi R, Cazzaniga NE, De Gaetani CI, et al (2018) Estimating and Comparing Dam Deformation Using Classical and GNSS Techniques. *Sensors* 2018, Vol 18, Page 756 18:756. <https://doi.org/10.3390/s18030756>
- Bellone T, Dabove P, Manzino AM, Taglioretti C (2016) Real-time monitoring for fast deformations using GNSS low-cost receivers. *Geomatics, Natural Hazards and Risk* 7:458–470. <https://doi.org/10.1080/19475705.2014.966867>
- Benoit L, Briole P, Martin O, et al (2015) Monitoring landslide displacements with the Geocube wireless network of low-cost GPS. *Eng Geol* 195:111–121.
<https://doi.org/10.1016/J.ENGGEOL.2015.05.020>
- Biagi L, Grec F, Negretti M (2016a) Low-cost GNSS receivers for local monitoring: Experimental simulation, and analysis of displacementsxs. *Sensors (Switzerland)* 16:.
<https://doi.org/10.3390/S16122140>
- Biagi L, Grec F, Negretti M (2016b) Low-cost GNSS receivers for local monitoring: Experimental simulation, and analysis of displacementsxs. *Sensors (Switzerland)* 16:.
<https://doi.org/10.3390/S16122140>
- Caldera S, Barindelli S, Sansò F, Pardi L (2022) Monitoring of Structures and Infrastructures by Low-Cost GNSS Receivers. *Applied Sciences* 2022, Vol 12, Page 12468 12:12468.
<https://doi.org/10.3390/APP122312468>
- Caldera S, Realini E, Barzaghi R, et al (2016) Experimental study on low-cost satellite-based geodetic monitoring over short baselines. *J Surv Eng* 142:.
[https://doi.org/10.1061/\(asce\)su.1943-5428.0000168](https://doi.org/10.1061/(asce)su.1943-5428.0000168)

- Chen KG, Wang JH, Huang BS, et al (2012) Vibrations of the TAIPEI 101 skyscraper caused by the 2011 Tohoku earthquake, Japan. *Earth, Planets and Space* 64:1277–1286. <https://doi.org/10.5047/EPS.2012.04.004/FIGURES/9>
- Chen Y, Guéguen P, Chen KH, et al (2023) Dynamic Characteristics of TAIPEI 101 Skyscraper from Rotational and Translation Seismometers. *Bulletin of the Seismological Society of America* 113:690–709. <https://doi.org/10.1785/0120220147>
- Cina A, Piras M (2015) Performance of low-cost GNSS receiver for landslides monitoring: test and results. *Geomatics, Natural Hazards and Risk* 6:497–514. <https://doi.org/10.1080/19475705.2014.889046>
- Everett T, Taylor T, Lee DK, Akos DM (2022) Optimizing the Use of RTKLIB for Smartphone-Based GNSS Measurements. *Sensors* 2022, Vol 22, Page 3825 22:3825. <https://doi.org/10.3390/S22103825>
- Häberling S, Rothacher M, Zhang Y, et al (2015) Assessment of high-rate GPS using a single-axis shake table. *J Geod* 89:697–709. <https://doi.org/10.1007/S00190-015-0808-2>
- Hamza V, Stopar B, Ambrožič T, et al (2020a) Testing Multi-Frequency Low-Cost GNSS Receivers for Geodetic Monitoring Purposes. *Sensors* 2020, Vol 20, Page 4375 20:4375. <https://doi.org/10.3390/S20164375>
- Hamza V, Stopar B, Ambrožič T, et al (2020b) Testing Multi-Frequency Low-Cost GNSS Receivers for Geodetic Monitoring Purposes. *Sensors* 2020, Vol 20, Page 4375 20:4375. <https://doi.org/10.3390/S20164375>
- Hamza V, Stopar B, Sterle O, Pavlovčič-Prešeren P (2023) A Cost-Effective GNSS Solution for Continuous Monitoring of Landslides. *Remote Sensing* 2023, Vol 15, Page 2287 15:2287. <https://doi.org/10.3390/RS15092287>
- He X, Yang G, Ding X, Chen Y (2004) Application and evaluation of a GPS multi-antenna system for dam deformation monitoring. *Earth, Planets and Space* 56:1035–1039. <https://doi.org/10.1186/BF03352545>
- Hu J, Li Z, Zhao Z, et al (2022) Full-Scale Measurements of Translational and Torsional Dynamics Characteristics of a High-Rise Building during Typhoon Sarika. *Materials* 2022, Vol 15, Page 493 15:493. <https://doi.org/10.3390/ma15020493>

- Jayamanne J, Psimoulis P, Owen J, et al (2025) Incorporating Low-Cost GNSS Receivers for Deformation Monitoring in High-Rise Buildings
- Kijewski-Correa T, Pirnia JD (2007) Dynamic behavior of tall buildings under wind: Insights from full-scale monitoring. *Structural Design of Tall and Special Buildings* 16:471–486. <https://doi.org/10.1002/TAL.415>;WGROUP:STRING:PUBLICATION
- Kubo N, Kobayashi K, Hsu LT, Amai O (2017) Multipath mitigation technique under strong multipath environment using multiple antennas. *ar* 49:75–82. <https://doi.org/10.6125/17-0130-928>
- Lotfabadi P (2014) High-rise buildings and environmental factors. *Renewable and Sustainable Energy Reviews* 38:285–295. <https://doi.org/10.1016/j.rser.2014.05.024>
- Meng X, Nguyen D, Owen J, et al Application of GeoSHM system in monitoring extreme wind events at the forth Road Bridge. *mdpi.com*X Meng, DT Nguyen, JS Owen, Y Xie, P Psimoulis, G YeRemote Sensing, 2019•mdpi.com
- Moschas F, Psimoulis PA, Stiros SC (2013) GPS/RTS data fusion to overcome signal deficiencies in certain bridge dynamic monitoring projects. *Smart Struct Syst* 12:1738–1991. https://doi.org/10.12989/sss.2013.12.3_4.251
- Moschas F, Stiros S (2011) Measurement of the dynamic displacements and of the modal frequencies of a short-span pedestrian bridge using GPS and an accelerometer. *Eng Struct* 33:10–17. <https://doi.org/10.1016/J.ENGSTRUCT.2010.09.013>
- Msaewe HA, Hancock CM, Psimoulis PA, et al (2017) Investigating multi-GNSS performance in the UK and China based on a zero-baseline measurement approach. *Measurement* 102:186–199. <https://doi.org/10.1016/J.MEASUREMENT.2017.02.004>
- Nickitopoulou A, Protopsalti K, Stiros S (2006) Monitoring dynamic and quasi-static deformations of large flexible engineering structures with GPS: Accuracy, limitations and promises. *Eng Struct* 28:1471–1482. <https://doi.org/10.1016/J.ENGSTRUCT.2006.02.001>
- Odolinski R, Teunissen PJG (2017) Low-cost, 4-system, precise GNSS positioning: A GPS, Galileo, BDS and QZSS ionosphere-weighted RTK analysis. *Meas Sci Technol* 28:. <https://doi.org/10.1088/1361-6501/AA92EB>

Park HS, Sohn HG, Kim IS, Park JH (2008) Application of GPS to monitoring of wind-induced responses of high-rise buildings. *The Structural Design of Tall and Special Buildings* 17:117–132. <https://doi.org/10.1002/TAL.335>

Patnana V, Rai DC (2022) Experimental testing on nonstructural continuous plasterboard suspended ceiling systems under shake table-generated motions. *Earthquake Spectra* 38:1918–1945. https://doi.org/10.1177/87552930221085298/ASSET/FD379DBA-4DFA-48CF-8151-ECBC13F50FB4/ASSETS/IMAGES/LARGE/10.1177_87552930221085298-FIG18.JPG

Peppas I, Psimoulis P, Meng X (2017) Using the signal-to-noise ratio of GPS records to detect motion of structures. <https://doi.org/10.1002/stc.2080>

Psimoulis P, Pytharoulis S, Karambalis D, Stiros S (2008a) Potential of Global Positioning System (GPS) to measure frequencies of oscillations of engineering structures. *J Sound Vib* 318:606–623. <https://doi.org/10.1016/J.JSV.2008.04.036>

Psimoulis P, Pytharoulis S, Karambalis D, Stiros S (2008b) Potential of Global Positioning System (GPS) to measure frequencies of oscillations of engineering structures. *J Sound Vib* 318:606–623. <https://doi.org/10.1016/J.JSV.2008.04.036>

Psimoulis PA, Stiros SC (2013) Measuring Deflections of a Short-Span Railway Bridge Using a Robotic Total Station. *Journal of Bridge Engineering* 18:182–185. [https://doi.org/10.1061/\(ASCE\)BE.1943-5592.0000334](https://doi.org/10.1061/(ASCE)BE.1943-5592.0000334)

Quesada-Olmo N, Jimenez-Martinez MJ, Farjas-Abadia M (2018a) Real-time high-rise building monitoring system using global navigation satellite system technology. *Measurement* 123:115–124. <https://doi.org/10.1016/j.measurement.2018.03.054>

Quesada-Olmo N, Jimenez-Martinez MJ, Farjas-Abadia M (2018b) Real-time high-rise building monitoring system using global navigation satellite system technology. <https://doi.org/10.1016/j.measurement.2018.03.054>

Roque D, José ;, Lima N, et al (2021) Integrated InSAR and GNSS Monitoring Subsystem for an Arch Dam and Reservoir Banks. *Journal of Surveying Engineering* 147:05021003. [https://doi.org/10.1061/\(asce\)su.1943-5428.0000361](https://doi.org/10.1061/(asce)su.1943-5428.0000361)

- Su JZ, Xia Y, Zhu LD, et al (2017) Typhoon- and temperature-induced quasi-static responses of a supertall structure. *Eng Struct* 143:91–100.
<https://doi.org/10.1016/j.engstruct.2017.04.007>
- Sun M, Li Q, Li Y (2022) Investigation of time-varying natural frequencies of high-rise buildings under harsh excitations using a high-resolution combined scheme. *Journal of Building Engineering* 57:104859. <https://doi.org/10.1016/j.jobbe.2022.104859>
- Wanninger L (2011) Carrier-phase inter-frequency biases of GLONASS receivers. *Journal of Geodesy* 2011 86:2 86:139–148. <https://doi.org/10.1007/S00190-011-0502-Y>
- Xiao R, Shi H, He X, et al (2019) Deformation monitoring of reservoir dams using GNSS: An application to south-to-north water diversion project, China. *IEEE Access* 7:54981–54992. <https://doi.org/10.1109/ACCESS.2019.2912143>
- Xie J, Cui X, Liu C, Liu T (2013) Analysis technique of signal bandwidth for GNSS. *IET Conference Publications* 2013:168–171.
<https://doi.org/10.1049/CP.2013.2401;PAGE:STRING:ARTICLE/CHAPTER>
- Xue C, Psimoulis P, Horsfall A, et al (2023) Assessment of the accuracy of low-cost multi-GNSS receivers in monitoring dynamic response of structures. *Applied Geomatics* 15:315–326. <https://doi.org/10.1007/S12518-022-00482-8/FIGURES/16>
- Xue C, Psimoulis PA (2023) Monitoring the dynamic response of a pedestrian bridge by using low-cost GNSS receivers. *Eng Struct* 284:115993.
<https://doi.org/10.1016/J.ENGSTRUCT.2023.115993>
- Xue C, Psimoulis PA, Meng X (2022) Feasibility analysis of the performance of low-cost GNSS receivers in monitoring dynamic motion. *Measurement* 202:111819.
<https://doi.org/10.1016/J.MEASUREMENT.2022.111819>
- Yi TH, Li HN, Gu M (2013) Recent research and applications of GPS-based monitoring technology for high-rise structures. *Struct Control Health Monit* 20:649–670.
<https://doi.org/10.1002/STC.1501>
- Yuan S (2021) High-Rise Building Deformation Monitoring Based on Remote Wireless Sensor Network. *IEEE Sens J* 21:25133–25141.
<https://doi.org/10.1109/JSEN.2021.3067378>

- Zhang L, Hu X, Xie Z, et al (2020) Field measurement study on time-varying characteristics of modal parameters of super high-rise buildings during super typhoon. *Journal of Wind Engineering and Industrial Aerodynamics* 200:.
<https://doi.org/10.1016/J.JWEIA.2020.104139>
- Zhang X, Zhang Y, Li B, Qiu G (2018a) GNSS-Based Verticality Monitoring of Super-Tall Buildings. *Applied Sciences* 2018, Vol 8, Page 991 8:991.
<https://doi.org/10.3390/app8060991>
- Zhang X, Zhang Y, Li B, Qiu G (2018b) GNSS-Based Verticality Monitoring of Super-Tall Buildings. *Applied Sciences* 2018, Vol 8, Page 991 8:991.
<https://doi.org/10.3390/APP8060991>
- Zhou LF, Ma PF, Xia Y, Xie CH (2018) MONITORING THE DEFORMATION OF HIGH-RISE BUILDINGS IN SHANGHAI LUIJIAZUI ZONE BY TOMO-PSINSAR. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XLII–3:2535–2539*. <https://doi.org/10.5194/ISPRS-ARCHIVES-XLII-3-2535-2018>

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupplementaryMaterialsJayamanneetal..docx](#)