DOI: 10.3217/978-3-99161-057-1-058

Monitoring Slow and Dynamic Deformations of High-Rise Buildings Using Low-Cost GNSS Receivers

JMO Jayamanne[1], PA Psimoulis [1], J Owen[1], NT Penna[2], C Xue[1]
[1]Faculty of Engineering, University of Nottingham, Nottingham, UK
[2]School of Engineering, Newcastle University, Newcastle, UK
jaymanne.jayamanne@nottingham.ac.uk

ABSTRACT: The structural integrity and safety of high-rise buildings rely heavily on effective deformation monitoring. Global Navigation Satellite System (GNSS) techniques are frequently utilized to monitor these deformations; yet, despite their great accuracy, they possess possible limitations due to high costs. Thus, this research investigates the potential of low-cost GNSS receivers for monitoring deformations in high-rise structures. The study focuses on incorporating low-cost GNSS receivers to capture slow motion movements caused by factors such as solar radiation and temperature fluctuations as well as dynamic movements induced by forces including wind loads and seismic forces. The performance of low-cost GNSS receivers is assessed against high-precision geodetic-grade GNSS receivers through a series of experiments conducted on a high-rise building under both slow-motion and dynamic conditions. The study primarily investigates the U-blox F9P dual-frequency GNSS receiver with Leica AS10, Tallysman TWI, and U-blox patch antennas. Results indicate that low-cost GNSS receivers demonstrate significant potential for capturing accurate and precise deformation measurements. The selection of GNSS antenna is found to significantly influence the overall quality of the GNSS data. However, the results indicate that with proper configuration, these low-cost receivers can be successfully integrated to develop an efficient and sustainable deformation monitoring system for high-rise buildings.

KEY WORDS: High-rise buildings; geodetic monitoring; Low-cost GNSS

1 INTRODUCTION

Structural Health Monitoring (SHM) is vital for ensuring safety, maintenance, and structural integrity of infrastructure. Structural Health Monitoring (SHM) facilitates continuing observation of structural performance, allowing for early problem detection, hence reducing the likelihood of failure and lowering maintenance costs. The necessity to implement novel SHM systems becomes critical as rapid urban expansion leads to significant structural development across the world [1], [2].

High rise buildings in particular, are exposed to both slow and dynamic deformations which necessitates for specialised monitoring techniques [3]. High-rise structures undergo continuous slow movements due to factors such as solar radiation and dynamic movements due to wind load and seismic activities. The conventional monitoring approaches for high-rise buildings require expensive installation efforts, along with other significant expenses and requirements such as time, physical and human resources [4].

Global Navigation Satellite Systems (GNSS) have emerged as a better option for deformation monitoring in recent decades, owing to advancements in high-quality GNSS receivers and effective processing techniques [5], [6]. GNSS-based monitoring systems now provide a precise system to observe both static and dynamic movements of structures [7], [8]. GNSS acquires multiple satellite signals to determine accurate positional coordinates, thereby facilitating the effective collection of long-term deformations, while simultaneously monitoring real-time dynamic motions. Modern geodetic grade GNSS receivers equipped with dual-frequency capability mitigate atmospheric errors and improve their accuracy in location measurement [9]. High-rate GNSS receivers provide data acquisition exceeding 10 Hz, hence enabling the observation of sudden structural displacements during events such as earthquakes and wind-related phenomena [10]. GNSS operates more effectively in conjunction with other sensors, such as accelerometers, as it enhances monitoring precision and accuracy. However, the significant high cost of a GNSS monitoring station which will allow mm level positioning, limit their application in deformation monitoring applications [9], [11], [12].

Low-cost GNSS receivers have emerged as a viable alternative for structural monitoring. These receivers, considerably more economical than geodetic-grade alternatives, include dual-frequency functionality that improves positioning precision and reduce atmospheric errors [7], [9], [11]. Recent improvements in low-cost GNSS technology have resulted in the creation of multi-constellation receivers that employ signals from GPS, GLONASS, Galileo, and BeiDou to enhance positional precision and signal accessibility in urban settings [13]. The cost-effectiveness of these receivers, typically priced under £500, renders them a practical option for extensive implementation in structural monitoring applications. This is evidenced by the findings of several researchers who have utilized low-cost receivers for monitoring deformations of bridges and other infrastructure [9], [11], [14].

Experimental validation is essential to evaluate the feasibility of low-cost GNSS receivers for monitoring both slow and dynamic deformations in tall buildings. Prior research has illustrated the effective utilisation of low-cost GNSS for bridge

CC BY 4.0
https://creativecommons.org/licenses/by/4.0/deed.en
This CC license does not apply to third party material and content noted otherwise

DOI: 10.3217/978-3-99161-057-1-058

monitoring, emphasising its capability for monitoring structural displacements. Researchers have employed low-cost GNSS receivers to observe the deformation and oscillation of suspension and cable-stayed bridges, attaining sub-centimeter precision in both static and dynamic assessments. Recent studies indicates that employing suitable data processing methodologies, including Precise Point Positioning (PPP) and Real-Time Kinematic (RTK) corrections, enables low-cost GNSS to yield accurate displacement measurements equivalent to those from high-end geodetic GNSS receivers [7], [9], [11].

Despite considerable advancements in bridge applications, the accuracy of low-cost GNSS in high-rise structural health monitoring remains mostly unexamined. High-rise structures present additional obstacles, including multipath effects, signal obstructions, and dynamic loading conditions, requiring further investigation to evaluate the reliability and accuracy of low-cost GNSS in this context [15], [16]. This study attempts to assess the performance of low-cost dual-frequency GNSS receivers in monitoring the deformations of high-rise buildings and to compare their findings with geodetic grade GNSS receivers and other traditional surveying techniques such as total station-based monitoring.

Thus, the ultimate objective of this study is to assess the feasibility of low-cost GNSS receivers in high-rise structural health monitoring, hence advancing the creation of low-cost and sustainable monitoring solutions. The results will offer significant insights into their precision, accuracy, and limitations supporting further developments in SHM technology.

2 SLOW MOVEMENT SIMULATION

This experiment aimed to assess the performance of a low-cost GNSS system during periodic horizontal displacements. The Tallysman TWI low-cost GNSS antenna was evaluated using a low-cost receiver (U-blox F9P) through the experiment.

The Tallysman TWI antenna is engineered to provide precise GNSS performance in low-cost applications. It has a compact, lightweight design and facilitates multi-constellation, dual-frequency signal reception, rendering it appropriate for high-precision positioning. The durable design guarantees reliable signal quality and phase centre stability, crucial for applications necessitating precise and reproducible measurements [17], [18]. The U-blox F9P is a high-performance, low-cost GNSS receiver that facilitates multi-band and multi-constellation tracking, encompassing GPS, GLONASS, Galileo, and BeiDou. Engineered for accurate positioning applications, it provides real-time kinematic (RTK) functionalities. U-blox receivers has been incorporated for several deformation monitoring observations in the recent past [19], [20].

The experimental set up comprised with a movement simulation device which was utilised to simulate 1 cm horizontal (along E-W axis) movements every hour. Dual frequency GNSS data were collected with 1 Hz sampling rate and the reference data were obtained through a Leica TS30 Robotic Total Station.

The experimental setup is depicted by figure 1.

Figure 1: Left- Tallysman TWI antenna and U-blox F9P receiver, Right: The movement simulation device

Collected data were processed through RTKlib processing software. RTKlib is an open-source software which has been utilised and validated in many GNSS applications and research [7], [9]. The software has been included into the analysis of GNSS data within the context of Structural Health Monitoring, owing to its capacity to assess carrier phase and pseudo range residuals. This enables users to gain a thorough comprehension of the quality of GNSS data and fluctuations in noise [21], [22], [23]. The following GNSS processing parameters were utilised in the post processing of the experimental data.

Parameter	**Value**
Processing mode	Kinematic (PPK)
Elevation mask	7°
Filter Type	Combined
Ephemeris	Broadcast
Ionospheric Correction	Broadcast
Tropospheric Correction	Saastamoinen

2.1 Analysis and Results

This study highlights the horizontal and vertical movements recorded by the Tallysman TWI low-cost GNSS antenna with the U-blox F9P low-cost GNSS receiver against the movements recorded by the Robotic Total Station. In figure 2 and 3 is depicted the horizontal and vertical movement time series of the Tallysman antenna for different satellite combinations as GPS only, GPS and Galileo and GPS, Galileo and Beidou.

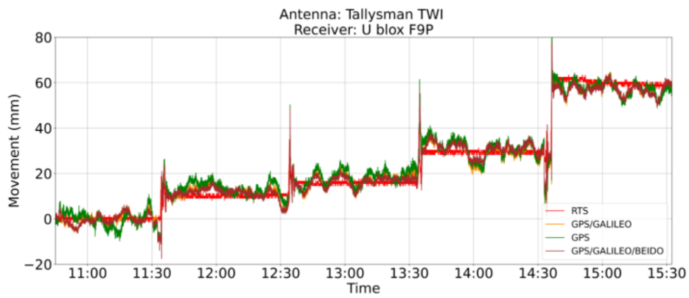


Figure 2: Horizontal (E-W) movement recorded by the Tallysman TWI antenna connected to U-blox F9P low-cost GNSS Receiver for GPS only, GPS/Galileo, GPS/ Galileo and Beidou Satellite combinations.

CC BY 4.0
https://creativecommons.org/licenses/by/4.0/deed.en
This CC license does not apply to third party material and content noted otherwise

DOI: 10.3217/978-3-99161-057-1-058

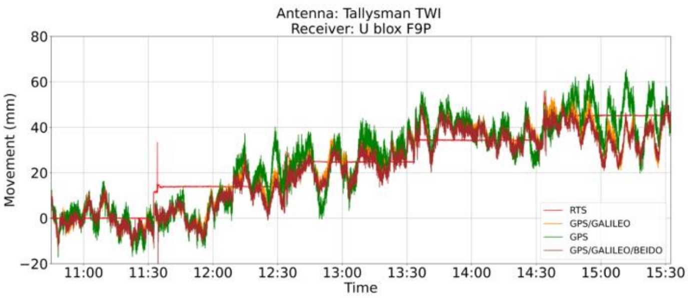


Figure 3: Vertical movement recorded by the Tallysman TWI antenna connected to U-blox F9P low-cost GNSS Receiver for GPS only, GPS/Galileo, GPS/ Galileo and Beidou Satellite combinations.

All satellite combinations follow a similar trend in both Horizontal and vertical movements. The vertical movement observations show a comparatively higher noise levels than the horizontal observations. The following mean errors have been obtained during each movement for the different configurations.

Movement	Error (mm)		
	GPS	GPS/GAL	GPS/GAL BDS
H 01	3.78	2.52	1.87
H 02	0.92	1.09	0.9
H 03	1.86	1.22	0.28
H 04	3.49	2.84	4
Mean	2.51	1.92	1.76
V 01	2.46	3.91	5.92
V 02	3.6	5.66	4.61
V 03	3.81	2.94	4.69
V 04	3.65	11.95 (outlier)	12.06 (outlier)
Mean	3.38	4.17	5.07

For horizontal movements, the results were evident by the mean errors where the combination of GPS, Galileo and Beidou signals showed the best performance for the GNSS setup. This agrees with the findings of other studies where the use of multiple satellite systems increase the number of visible satellites and the satellite geometry thereby minimizing the noise [24], [25].

However, for the vertical observations the use of GPS only provided the best performance compared to the other combinations. This may result from enhanced signal stability, well-defined orbital characteristics, and advanced error modelling of GPS, especially in the vertical dimension. Furthermore, multi-GNSS integration may result in inter-system biases and discrepancies in vertical positioning due to fluctuations in satellite elevation angles, hardware delays, and ionospheric delay modelling among various systems, thereby compromising vertical accuracy if not adequately corrected [26], [27], [28].

A Welch Power Spectral Density (PSD) analysis was conducted to further explain the noise characteristics of the GNSS set up. The Welch technique calculates a signal's power distribution by segmenting the data, applying a window function, and averaging the periodogram. In GNSS data analysis, Welch PSD is especially effective for identifying signal artefacts, multipath effects, or oscillator instabilities, which appear as frequency-specific abnormalities in the spectrum domain. The resultant spectrum discusses the fundamental noise structures, which is essential for enhancing the reliability and precision of satellite-based positioning systems [29], [30].

The Welch PSD of the Tallysman antenna for different satellite combinations as GPS only, GPS and Galileo Only and GPS, Galileo and Beidou for horizontal and vertical movements have been depicted in figures 4 and 5 respectively.

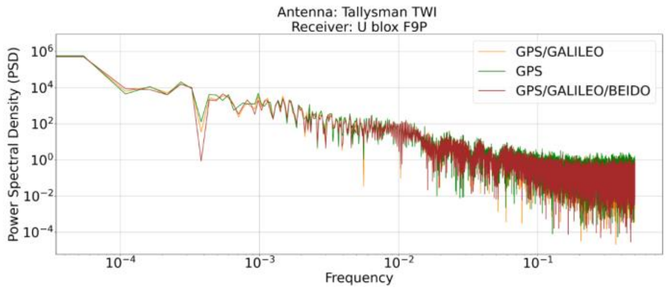


Figure 4: Welch PSD for horizontal (E-W) movement recorded by the Tallysman TWI antenna connected to U-blox F9P low-cost GNSS Receiver for GPS only, GPS/Galileo, GPS/ Galileo and Beidou Satellite combinations.

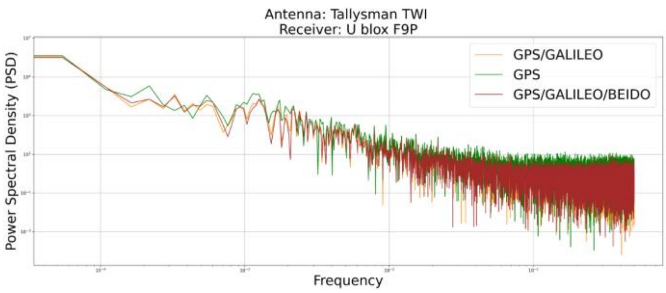


Figure 5: Welch PSD for vertical movement recorded by the Tallysman TWI antenna connected to U-blox F9P low-cost GNSS Receiver for GPS only, GPS/Galileo, GPS/ Galileo and Beidou Satellite combinations.

The PSD results further indicate that the integration of GPS, Galileo, and Beidou satellites will result in the least amount of noise. Thus, a combination of multiple satellite constellations is suggested for optimum results with Tallysman TWI low-cost antenna and the U-blox F9P low-cost GNSS receiver. However, further experimentation is necessary to assess the impact of atmospheric errors and multipath toward the low-cost antennas and further tests will be carried out to test different atmospheric models for a deeper performance and noise analysis.

CC BY 4.0
https://creativecommons.org/licenses/by/4.0/deed.en
This CC license does not apply to third party material and content noted otherwise

DOI: 10.3217/978-3-99161-057-1-058

3 DYNAMIC MOVEMENT SIMULATION

A dynamic movement simulation test was conducted to assess the performance of Tallysman Antenna with the U-blox F9P receiver. This test was conducted through controlled vibrations of specific frequency range, incorporating the APS 113 shaker [31]. The APS 113 is a long-stroke, air-bearing electrodynamic shaker designed for the precise calibration and evaluation motion transducers. It delivers a force output of 133 N and a peak-to-peak displacement of 158 mm, operating within a frequency range up to 200 Hz. The air-bearing system ensures minimum friction, hence diminishing noise and distortion. Through the shaker a controlled vibratory platform was introduced to simulate a real-world oscillation [32].

The Tallysman TWI antenna was tested with the U-blox F9P receiver for vibrations at frequencies of 0.1 Hz and 0.25 Hz, produced by an analogue signal generator. The selection of low-frequency simulations aimed to recreate long-range oscillations, which are the primary vibrations of high-rise buildings caused by wind load. Three vibration amplitudes in the E-W direction (i) below 1 cm (ii) around 2-3 cm, and (iii) around 6-7 cm were manually introduced for 10 minutes. The accuracy of the GNSS data were determined through the E-W amplitudes compared against the measurements collected through LeicaTS30 Robotic Total Station. Same observation and processing parameters as the slow movement simulation test were utilised for this test.

Figure 6: Left- The APS 113 shaker used for the experiment with Tallysman TWI, U-blox Patch and Leica AS10 Geodetic antennas. Right- U-blox F9P receivers connected to the antennas and Raspberry Pi devices to log the data.

3.1 Analysis and Results

Displacement time series were obtained for the three introduced amplitude values. The exact oscillating amplitude cannot be controlled by the APS 113 shaker hence, the amplitudes were manually controlled and the RTS observation was taken as the reference amplitude [33].

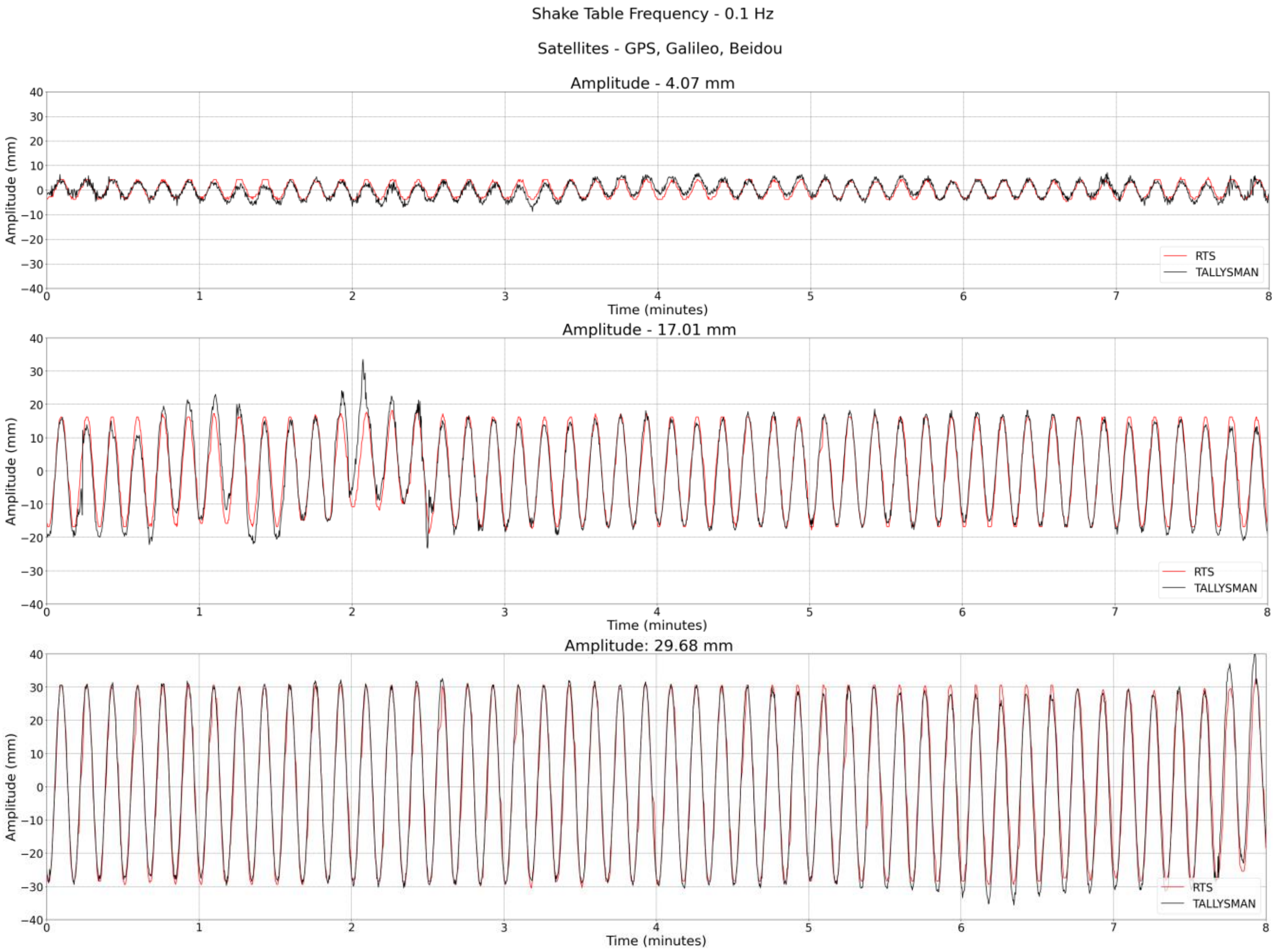


Figure 7: The amplitudes recorded by the Tallysman TWI antenna connected to U-blox F9P low-cost GNSS Receiver for 0.1 Hz shake table oscillation.

CC BY 4.0
https://creativecommons.org/licenses/by/4.0/deed.en
This CC license does not apply to third party material and content noted otherwise

 DOI: 10.3217/978-3-99161-057-1-058

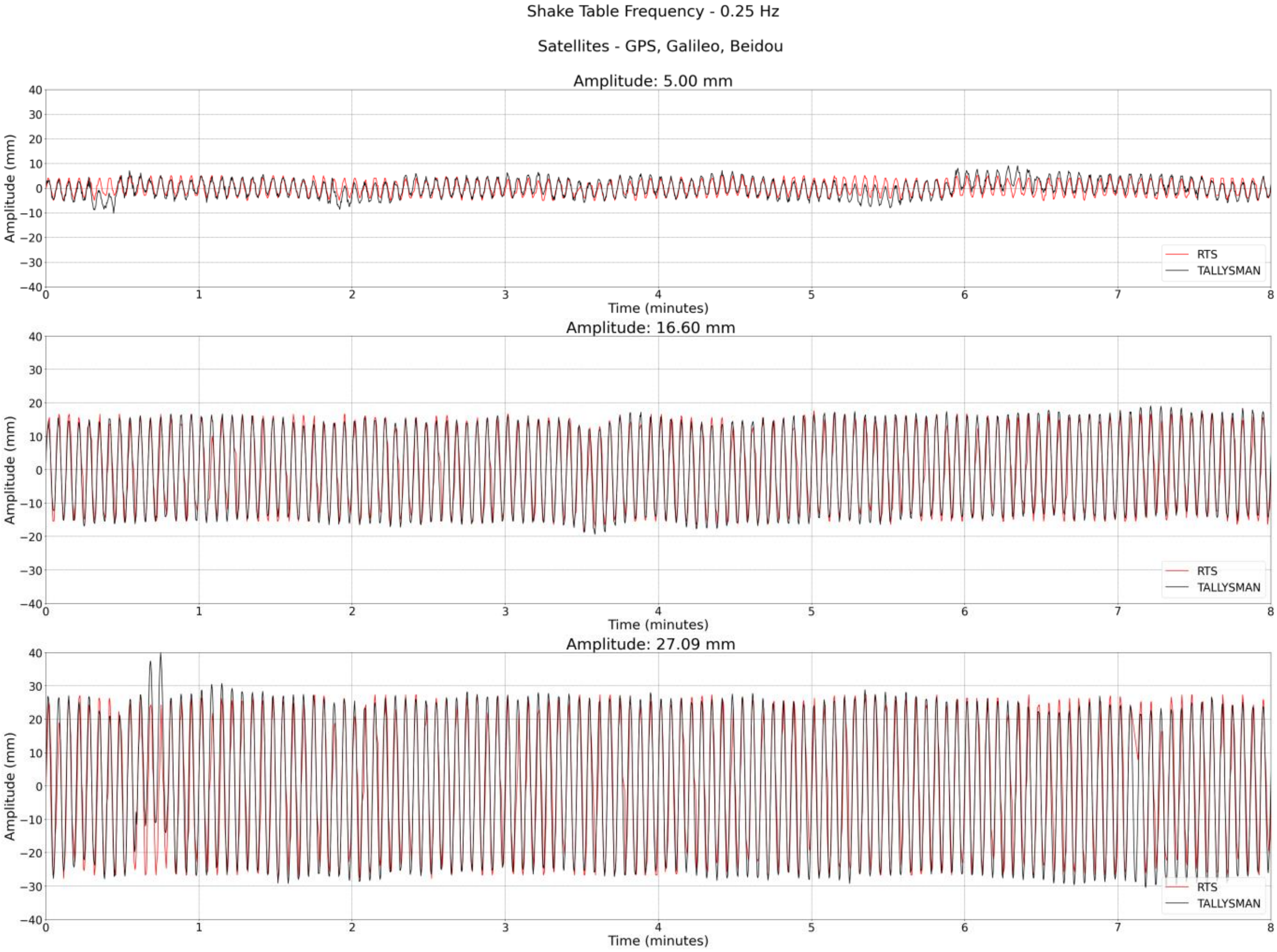


Figure 8: The amplitudes recorded by the Tallysman TWI antenna connected to U-blox F9P low-cost GNSS Receiver for 0.25 Hz shake table oscillation.

Figures 7 and 8 depict the displacement time series at frequencies of 0.1 Hz and 0.25 Hz, respectively. The results indicate that the Tallysman antenna closely replicates the displacement achieved by the RTS. Further, the mean errors of positive and negative peaks were determined to provide further insight into the noise levels. The overall absolute error recorded by the Tallysman antenna with U-blox receiver is 0.6 mm for 0.1 Hz oscillation and 2.5 mm for 0.25 Hz oscillation.

The mean error of each amplitude value can be summarised as follows:

	Amplitude (mm)		**Absolute Error (mm)**
	RTS (Reference)	**Tallysman** (Observed)	
0.1 Hz	4.1	3.3	0.8
	17.0	16.4	0.6
	29.7	30.1	0.4
0.25 Hz	5.0	7.8	2.8
	16.6	17.6	1.0
	27.1	30.6	3.5

The mean amplitude values obtained from the Tallysman- U blox low-cost GNSS configuration validate the feasibility of utilising such systems for monitoring dynamic movements.

4 CASE STUDY

A preliminary case study was performed on a 220-meter-high residential building utilising a low-cost GNSS setup that included a Tallysman antenna and a U-blox F9P receiver. The building, a concrete-steel composite construction, serves as an effective testbed for structural monitoring because of its vulnerability to deformation under environmental pressures.

In high-rise structures, the variations of solar radiations and wind forces are among the most significant factors influencing structural performance [1]. Thermal impacts induce differential expansion between concrete and steel, potentially leading to internal tensions and long-term deformations due to the disparity in thermal expansion coefficients [1], [34]. The impacts are particularly evident in composite systems, where restricted expansion can result in cracking or the accumulation of residual strain over time. Wind-induced lateral loads concurrently create building wobble and oscillations, which compromise structural stability and affect serviceability and

CC BY 4.0
https://creativecommons.org/licenses/by/4.0/deed.en
This CC license does not apply to third party material and content noted otherwise

DOI: 10.3217/978-3-99161-057-1-058

occupant comfort [35], [36], [37]. Comprehending these environmental factors is crucial for the advancement of resilient high-rise structures and facilitates the larger incorporation of low-cost GNSS as an effective instrument for structural health monitoring.

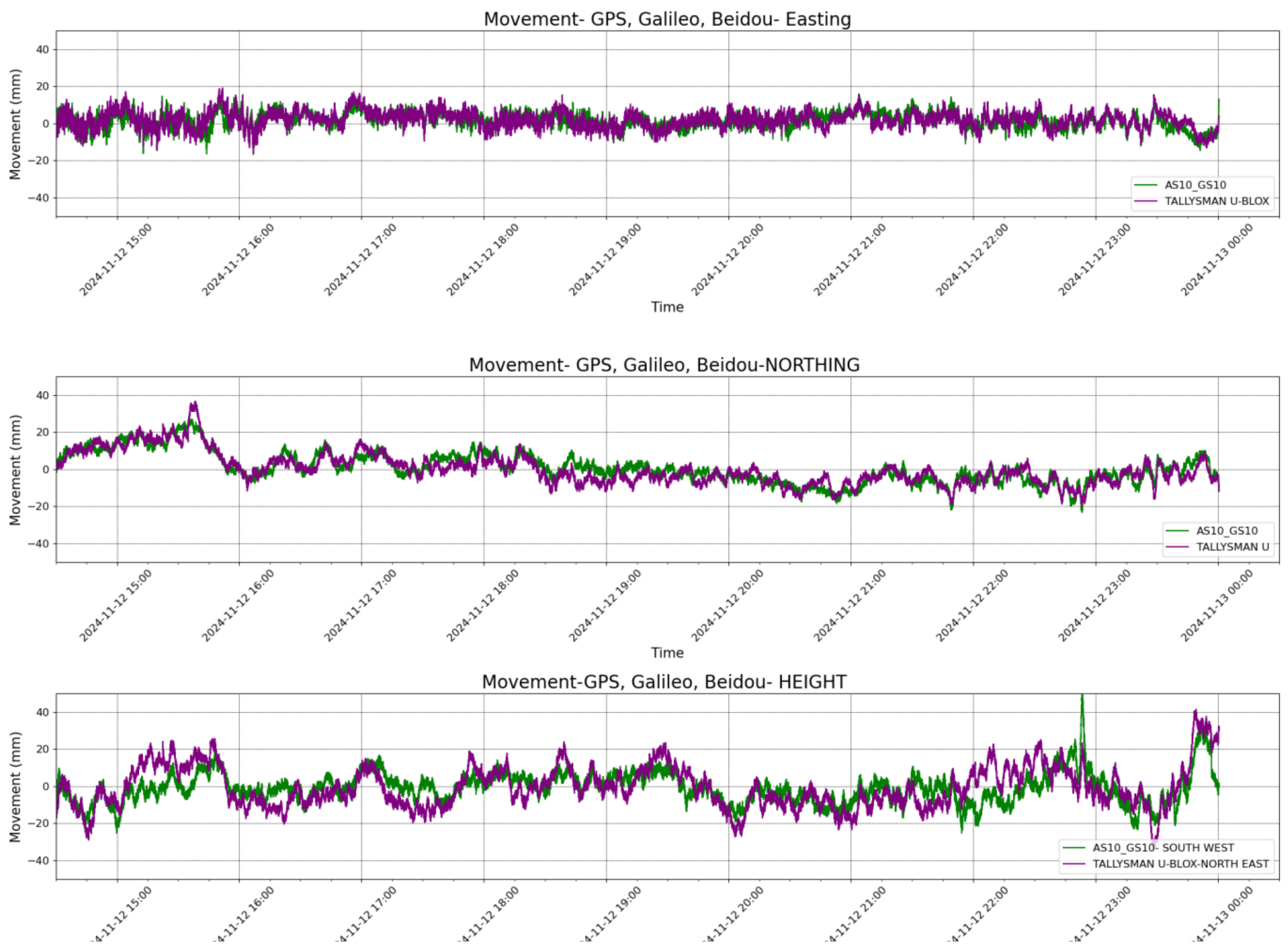
Data for this case study were gathered using an 11-hour, 1 Hz GNSS data collection conducted on the building's rooftop. The reference data were acquired using a full geodetic GNSS configuration consisting of a Leica AS10 antenna and a Leica AS10 receiver. The rover stations were strategically positioned to minimize multipath interference, which is a common challenge in GNSS measurements due to signal reflection from nearby surfaces such as walls, windows, or metallic structures. To mitigate multipath errors, several strategies were implemented during the setup and data collection phases. First, the rooftop was chosen as the primary location to ensure a clear line of sight to the satellites and to minimize the presence of reflective surfaces in the vicinity. The GNSS antennas were mounted on the handrails of the building with sufficient height to reduce signal reflection from the ground.

During the planning stage, satellite geometry and the surrounding environment were carefully analysed using software-based sky plots to select observation periods with optimal satellite visibility and reduced likelihood of low-angle reflections. The rover stations were placed at locations with minimal obstruction and reflective surfaces, avoiding proximity to glass façades or metallic rooftops that could induce strong signal reflections. While these strategies significantly reduced the impact of multipath interference, it should be noted that completely eliminating multipath is unfeasible in real-world settings, particularly in urban or semi-urban environments.

Figure 9: Tallysman TWI antenna connected to the handrail of the building rooftop. Right- U-blox F9P receiver connected to the antenna and Raspberry Pi device to log the data.

4.1 Analysis and Results

The data were post-processed via a short baseline double difference solution through RTKlib software. The Base Station is a continuously operating reference station (CORS) equipped



CC BY 4.0
https://creativecommons.org/licenses/by/4.0/deed.en
This CC license does not apply to third party material and content noted otherwise

DOI: 10.3217/978-3-99161-057-1-058

with a full geodetic setup and a baseline distance of 5.1 km. A time series analysis is conducted for the GPS, Galileo and Beidou satellite constellations to identify the positional variations in Northing, Easting and Height components of the monitoring points. As depicted by the time series in figure 10, the Tallysman antenna combined with the U-blox receiver demonstrates precision comparable to that of a full geodetic configuration. Although a dataset of 10 hours is inadequate for delivering comprehensive information into building movement, it sufficiently illustrates the potential of the low-cost system. This is further demonstrated by the following standard deviation values.

	Standard Deviation (mm)		
	E	N	H
Low-cost	4.50	8.50	11.31
Geodetic	4.23	8.08	7.63
Difference	0.27	0.42	3.68

For the further understanding of the long-term variations in position, a moving average was calculated for a rolling window of 300s (5 minutes).

Figure 11: Moving average variation of the low-cost system and fully geodetic system.

Based on figure 11, it is evident that the low-cost GNSS setup share the similar trend as the geodetic setup. Adhering to the same trend suggests that the temporal variations and directional changes observable in the positional data of both configurations demonstrate similarly over time—indicating that, despite variation in accuracy, the low-cost setup can capture the same movement patterns and positional dynamics as the high-precision geodetic reference.

However, further testing on high-rise buildings is needed to assess the performance of low-cost GNSS systems over long-term deployments. Short-term tests do not capture the gradual effects of component wear, thermal drift, or mounting stability issues that may reduce accuracy over time. Weather conditions such as heavy rain, snow, or high winds can also impact signal quality by causing attenuation, multipath reflections, or antenna

CC BY 4.0
https://creativecommons.org/licenses/by/4.0/deed.en
This CC license does not apply to third party material and content noted otherwise

DOI: 10.3217/978-3-99161-057-1-058

movement. In addition, variations in the ionosphere and troposphere can introduce delays that low-cost receivers may not correct effectively. Long-term studies under different weather and seasonal conditions are therefore essential to better understand noise levels and reliability, and to guide improvements in system design and calibration.

5 CONCLUSION AND FUTURE DIRECTIONS

This paper presented the results of control experiments testing Tallysman TWI low-cost GNSS antenna with U-blox F9P dual frequency low-cost GNSS receiver in slow moving conditions and dynamic motion conditions. It further presented results from an initial case study conducted on a high-rise building testing the low-cost system.

The results indicate that the low-cost system can reach a comparable precision with the geodetic systems and can obtain sub-centemeter accuracy through rigorous observation and processing methods, such as the use of multiple satellite constellations for observations [7], [9]. The horizontal component can reach an accuracy of less than 5mm for both slow motion and dynamic motion conditions which depicts the potential of low-cost systems in achieving a sub-centimeter accuracy. The noise levels in the vertical component are generally higher than that of the horizontal movements, however, they are still less than a couple of centimeters.

The case study on the building further demonstrates the efficiency of low-cost systems, since they exhibit comparable accuracy and precision to full geodetic configurations in practical scenarios when atmospheric and multipath challenges are not completely mitigated. The findings of this work align with the results of other research on the utilisation of low-cost GNSS systems for monitoring deformations in flexible structures, such as tall buildings and bridges [7], [9], [14].

This work is part of an ongoing study evaluating various low-cost technologies under diverse atmospheric and environmental circumstances. Subsequent investigation will involve testing low-cost systems for long-term deformation observations across various environmental conditions and seasons. This will facilitate better understanding of the accuracy and precision of low-cost devices, as well as their suitability for long-term deployment. It will further evaluate the fluctuations in noise under various atmospheric circumstances, so facilitating the identification of methods to mitigate or minimise those errors.

ACKNOWLEDGMENTS

This research is funded by the EPSRC, UK through the Center for Doctoral Training in Geospatial Systems, with the grant reference EP/S023577/1.

REFERENCES

[1] Y. D. Hu, R. Hou, Q. Xia, and Y. Xia, ‘Temperature-induced displacement of supertall structures: A case study’, *Advances in Structural Engineering*, vol. 22, no. 4, pp. 982–996, Mar. 2019, doi: 10.1177/1369433218795288/ASSET/IMAGES/LARGE/10.1177_1369433218795288-FIG12.JPEG.

[2] J. Z. Su *et al.*, ‘Long-term structural performance monitoring system for the Shanghai Tower’, *J Civ Struct Health Monit*, vol. 3, no. 1, pp. 49–61, Feb. 2013, doi: 10.1007/S13349-012-0034-Z/FIGURES/16.

[3] M. G. Mustafin, V. A. Valkov, and A. I. Kazantsev, ‘Monitoring of Deformation Processes in Buildings and Structures in Metropolises’, *Procedia Eng*, vol. 189, pp. 729–736, Jan. 2017, doi: 10.1016/J.PROENG.2017.05.115.

[4] S. Yuan, ‘High-Rise Building Deformation Monitoring Based on Remote Wireless Sensor Network’, *IEEE Sens J*, vol. 21, no. 22, pp. 25133–25141, Nov. 2021, doi: 10.1109/JSEN.2021.3067378.

[5] C. O. Yigit, A. El-Mowafy, A. Anil Dindar, M. Bezcioglu, and I. Tiryakioglu, ‘Investigating Performance of High-Rate GNSS-PPP and PPP-AR for Structural Health Monitoring: Dynamic Tests on Shake Table’, *Journal of Surveying Engineering*, vol. 147, no. 1, p. 05020011, Feb. 2021, doi: 10.1061/(ASCE)SU.1943-5428.0000343/ASSET/8989E20D-C683-42F9-8C4B-89891B85CD09/ASSETS/IMAGES/LARGE/FIGURE16.JPG.

[6] P. Psimoulis, S. Pytharouli, D. Karambalis, and S. Stiros, “Potential of Global Positioning System (GPS) to measure frequencies of oscillations of engineering structures,” *Journal of Sound and Vibration*, vol. 318, no. 3, pp. 606–623, 2008.

[7] C. Xue, P. A. Psimoulis, and X. Meng, ‘Feasibility analysis of the performance of low-cost GNSS receivers in monitoring dynamic motion’, *Measurement*, vol. 202, p. 111819, Oct. 2022, doi: 10.1016/J.MEASUREMENT.2022.111819.

[8] J. Jayamanne, R. Vandebona, and J. Karalliyadda, ‘Optimization of Conventional Land Survey Techniques Using Modern Technology’, 2020, Accessed: Mar. 27, 2025. [Online]. Available: http://ir.kdu.ac.lk/handle/345/3258

[9] C. Xue, P. Psimoulis, A. Horsfall, Q. Zhang, and X. Meng, ‘Assessment of the accuracy of low-cost multi-GNSS receivers in monitoring dynamic response of structures’, *Applied Geomatics*, vol. 15, no. 2, pp. 315–326, Jun. 2023, doi: 10.1007/S12518-022-00482-8/FIGURES/16.

[10] J. Yu, X. Meng, B. Yan, B. Xu, Q. Fan, and Y. Xie, ‘Global Navigation Satellite System-based positioning technology for structural health monitoring: a review’, *Struct Control Health Monit*, vol. 27, no. 1, Jan. 2020, doi: 10.1002/STC.2467.

[11] C. Xue and P. A. Psimoulis, “Monitoring the dynamic response of a pedestrian bridge by using low-cost GNSS receivers,” *Engineering Structures*, vol. 284, p. 115993, 2023, doi: 10.1016/j.engstruct.2023.115993.

[12] S. Ogutcu, S. Alcay, H. Duman, B. Numan Ozdemir, and C. Konukseven, ‘Static and kinematic PPP-AR performance of low-cost GNSS receiver in monitoring displacements’, *Advances in Space Research*, vol. 72, no. 11, pp. 4795–4808, Dec. 2023, doi: 10.1016/J.ASR.2023.09.025.

[13] C. Xue, P. Psimoulis, Q. Zhang, and X. Meng, “Analysis of the performance of closely spaced low-cost multi-GNSS receivers,” *Applied Geomatics*, vol. 13, no. 3, pp. 415–435, 2021, doi: 10.1007/s12518-021-00366-3.

[14] A. Cina and M. Piras, ‘Performance of low-cost GNSS receiver for landslides monitoring: test and results’, *Geomatics, Natural Hazards and Risk*, vol. 6, no. 5–7, pp. 497–514, Jul. 2015, doi: 10.1080/19475705.2014.889046.

[15] F. Moschas, P. A. Psimoulis, and S. C. Stiros, “GPS/RTS data fusion to overcome signal deficiencies in certain bridge dynamic monitoring projects,” *Smart Structures and Systems*, vol. 12, no. 3–4, pp. 251–269, 2013, doi: 10.12989/sss.2013.12.3_4.251.

[16] I. Peppa and P. A. Psimoulis, “Detection of GNSS antenna oscillatory motion and multipath conditions via exploitation of multipath-induced SNR variations,” *GPS Solutions*, vol. 27, no. 3, p. 117, 2023, doi: 10.1007/s10291-023-01470-7.

[17] V. Hamza, B. Stopar, T. Ambrožič, G. Turk, and O. Sterle, ‘Testing Multi-Frequency Low-Cost GNSS Receivers for Geodetic Monitoring Purposes’, *Sensors 2020, Vol. 20, Page 4375*, vol. 20, no. 16, p. 4375, Aug. 2020, doi: 10.3390/S20164375.

[18] M. Khalil, F. Crenna, and G. B. Rossi, ‘GNSS Signals for Sea Wave Measurements’, *2024 IEEE International Workshop on Metrology for the Sea, MetroSea 2024 - Proceedings*, pp. 329–333, 2024, doi: 10.1109/METROSEA62823.2024.10765644.

[19] D. A. Kogogin, A. V. Sokolov, I. A. Nasyrov, V. O. Dementiev, and R. V. Zagretdinov, ‘Signal Receiver for Global Navigation Satellite Systems Based on a U-blox ZED-F9P Module for Ionospheric Research’, *Journal of Communications Technology and Electronics*, vol. 68, no. 6, pp. 682–691, Jun. 2023, doi: 10.1134/S1064226923060074/TABLES/2.

[20] R. Hohensinn *et al.*, ‘Low-Cost GNSS and Real-Time PPP: Assessing the Precision of the U-blox ZED-F9P for Kinematic Monitoring

CC BY 4.0
https://creativecommons.org/licenses/by/4.0/deed.en
This CC license does not apply to third party material and content noted otherwise

DOI: 10.3217/978-3-99161-057-1-058

Applications', *Remote Sens (Basel)*, vol. 14, no. 20, p. 5100, Oct. 2022, doi: 10.3390/RS14205100/S1.

[21] T. Takasu and A. Yasuda, 'Development of the low-cost RTK-GPS receiver with an open source program package RTKLIB'.

[22] T. Everett, T. Taylor, D. K. Lee, and D. M. Akos, 'Optimizing the Use of RTKLIB for Smartphone-Based GNSS Measurements', *Sensors 2022, Vol. 22, Page 3825*, vol. 22, no. 10, p. 3825, May 2022, doi: 10.3390/S22103825.

[23] J. Jayamanne, C. Perera, and R. Vandebona, 'Evaluating the applicability of Open Source GNSS Post-Processing Software for Applications of Surveying', 2019.

[24] S. Caldera, S. Barindelli, F. Sansò, and L. Pardi, 'Monitoring of Structures and Infrastructures by Low-Cost GNSS Receivers', *Applied Sciences 2022, Vol. 12, Page 12468*, vol. 12, no. 23, p. 12468, Dec. 2022, doi: 10.3390/APP122312468.

[25] L. Poluzzi, L. Tavasci, F. Corsini, M. Barbarella, and S. Gandolfi, 'Low-cost GNSS sensors for monitoring applications', *Applied Geomatics*, vol. 12, no. 1, pp. 35–44, Apr. 2020, doi: 10.1007/S12518-019-00268-5/FIGURES/13.

[26] N. Quesada-Olmo, M. J. Jimenez-Martinez, and M. Farjas-Abadia, 'Real-time high-rise building monitoring system using global navigation satellite system technology', 2018, doi: 10.1016/j.measurement.2018.03.054.

[27] S. Caldera, S. Barindelli, F. Sansò, and L. Pardi, 'Monitoring of Structures and Infrastructures by Low-Cost GNSS Receivers', *Applied Sciences 2022, Vol. 12, Page 12468*, vol. 12, no. 23, p. 12468, Dec. 2022, doi: 10.3390/APP122312468.

[28] T. H. Yi, H. N. Li, and M. Gu, 'Recent research and applications of GPS-based monitoring technology for high-rise structures', *Struct Control Health Monit*, vol. 20, no. 5, pp. 649–670, May 2013, doi: 10.1002/STC.1501.

[29] X. Jun, C. Xiaozhun, L. Chonghua, and L. Tianxiong, 'Analysis Technique of Signal Bandwidth for GNSS'.

[30] X. Niu *et al.*, 'Using Allan variance to analyze the error characteristics of GNSS positioning', *GPS Solutions*, vol. 18, no. 2, pp. 231–242, Apr. 2014, doi: 10.1007/S10291-013-0324-X/TABLES/10.

[31] G. Oku Topal and B. Akpinar, 'High rate GNSS kinematic PPP method performance for monitoring the engineering structures: Shake table tests under different satellite configurations', *Measurement*, vol. 189, p. 110451, Feb. 2022, doi: 10.1016/J.MEASUREMENT.2021.110451.

[32] V. Patnana and D. C. Rai, 'SEISMIC PERFORMANCE OF PLASTERBOARD SUSPENDED CEILINGS UNDER SHAKING-TABLE GENERATED MOTIONS'.

[33] P. A. Psimoulis and S. C. Stiros, 'Experimental Assessment of the Accuracy of GPS and RTS for the Determination of the Parameters of Oscillation of Major Structures', *Computer-Aided Civil and Infrastructure Engineering*, vol. 23, no. 5, pp. 389–403, Jul. 2008, doi: 10.1111/J.1467-8667.2008.00547.X.

[34] P. Breuer, T. Chmielewski, P. Górski, E. Konopka, and L. Tarczyński, 'The Stuttgart TV Tower-displacement of the top caused by the effects of sun and wind', *Eng Struct*, vol. 30, pp. 2771–2781, 2008, doi: 10.1016/j.engstruct.2008.03.008.

[35] O. & M. Preetam Biswas, Skidmore, *Tall Buildings for Wind*. 2020.

[36] Q. S. Li, L.-H. Zhi, A. Y. Tuan, C.-S. Kao, S.-C. Su, and C.-F. Wu, 'Dynamic Behavior of Taipei 101 Tower: Field Measurement and Numerical Analysis', *Journal of Structural Engineering*, vol. 137, no. 1, pp. 143–155, Jan. 2011, doi:10.1061/(ASCE)ST.1943-541X.0000264

[37] J. Wu, H. Xu, and Q. Zhang, 'Dynamic performance evaluation of Shanghai Tower under winds based on full-scale data', 2019, doi: 10.1002/tal.1611.

CC BY 4.0
https://creativecommons.org/licenses/by/4.0/deed.en
This CC license does not apply to third party material and content noted otherwise