Advances in Military Technology
Vol. 20, No. 2, 2025, pp. 529-547
ISSN 1802-2308, eISSN 2533-4123
DOI 10.3849/aimt.01913

Comparative Performance of GNSS Configurations in Malaysia: GPS, GLONASS, BeiDou, and Galileo

Y. Hwa Ho*, and D. Raku

Centre of Technology for Disaster Risk Reduction, Universiti Teknikal Malaysia Melaka, Malaysia

The manuscript was received on 14 August 2024 and was accepted after revision for publication as a case study on 9 December 2025.

Abstract:

This study investigates the performance of Global Navigation Satellite System (GNSS) configurations in Malaysia under both static and kinematic conditions. Data were collected using a U-blox NEO-M8N receiver to evaluate GPS, GLONASS, BeiDou, Galileo, and their combinations. Results indicate that the GPS+BeiDou configuration consistently outperforms others in terms of positioning accuracy, altitude stability, and trajectory consistency. Static analysis shows minimal coordinate dispersion and altitude fluctuation, while kinematic tests confirm robust performance in challenging environments with multipath effects. Dilution of precision (HDOP, VDOP, PDOP) metrics further validate the superior reliability of GPS+BeiDou. Overall, the findings highlight GPS+BeiDou as the optimal configuration for precise and reliable positioning in Malaysian environments.

Keywords:

Global Navigation Satellite System (GNSS), performance evaluation, position accuracy

1 Introduction

GNSS technology is integral to modern navigation and positioning applications. However, the performance of GNSS can be affected by various factors, including signal availability, accuracy, integrity, and environmental conditions. The challenge lies in evaluating these performance metrics effectively, especially in complex urban environments where signal obstruction and multipath effects are prevalent. The need for robust performance evaluation methods is underscored by the increasing deployment of GNSS in safety-critical applications, such as aviation and autonomous driving, where the consequences of GNSS failures can be severe.

* *Corresponding author: Centre of Technology for Disaster Risk Reduction (CDR), Universiti Teknikal Malaysia Melaka (UTeM), Malaysia. Phone: +606-270 2289, Fax: +606-270 104, E-mail: yihhwa@utem.edu.my. ORCID 0000-0002-9258-1513.*

Recent studies have focused on various aspects of GNSS performance evaluation, particularly in challenging environments. For instance, research has demonstrated that augmentation methods can enhance positioning accuracy in urban environments, where traditional GNSS signals may be compromised due to buildings and other obstacles. Additionally, the performance of different GNSS constellations, such as GPS, GLONASS, and Galileo, has been compared to identify optimal configurations for specific applications [1]. Moreover, innovative solutions like GNSS Foresight have been proposed to predict GNSS performance in real-time, allowing users to mitigate potential signal degradation [2].

Swaminathan et al. [3] evaluated the performance of position augmentation methods for autonomous vehicles in urban settings. The study highlighted the impact of different terrain types on GNSS signal availability and positioning accuracy, emphasizing the need for tailored augmentation strategies to enhance performance in dynamic environments. Another significant contribution to the field is the work by Hamza et al. [4], which assessed the performance of low-cost multi-frequency GNSS receivers. This research aimed to identify the displacement detection capabilities of these receivers, comparing them with traditional geodetic instruments. The findings demonstrated that low-cost receivers could achieve satisfactory performance levels for specific applications, thereby broadening the accessibility of GNSS technology.

In addition, the study by Wang et al. [5] explored the defensive performance evaluation methods of GNSS against jamming and spoofing attacks. This research is particularly relevant given the increasing threats to GNSS signals, which can compromise the reliability of navigation systems. The proposed evaluation framework aims to assess the resilience of GNSS under adverse conditions, providing insights into potential countermeasures.

Kubo [6] evaluated the performance of QZSS high-accuracy services like CLAS (QZSS L1-SAIF) and SLAS (QZSS L6-SAIF) in Japan. He found that CLAS can achieve 3 cm accuracy (95 %) and SLAS 1 m accuracy (95 %) for both static and kinematic scenarios. CLAS can substitute RTK in some cases. PPP showed 10–15 cm accuracy after convergence. Another study assessed the performance of MADOCA-PPP at 8 locations in Asia and Oceania, including Malaysia. It found the horizontal 95 % accuracy was around 10–20 cm. The results are suitable for evaluating PPP performance for moving platforms globally.

Cai et al. [7] reviewed standardization efforts and research methods for evaluating GNSS performance for railway applications. They mentioned that the Malaysian MASS network allows GPS data to be accessed with a 24+ hour delay. A study assessed GPS performance in Malaysia using the AUSPOS online GPS processing service. It found out that the nearest IGS reference stations are in Singapore, Philippines and Indonesia, which may limit the accuracy [8].

Pishehvari et al. [9] evaluated the performance of GNSS augmentation methods for autonomous vehicles in urban environments, focusing on the challenges posed by buildings, tunnels, and underpasses. Ng et al. [10] assessed the performance of RTK-GNSS navigation under different landscapes, including open sky, urban, and forested areas.

Recent studies have demonstrated the significant influence of environmental conditions on GNSS signal quality and positioning performance under dynamic scenarios. Rybanský et al. [11] conducted a comprehensive field investigation to evaluate GNSS accuracy in forested environments using kinematic observations. Their results revealed that vegetation density, canopy structure, and species composition substantially affect satellite visibility, dilution of precision (DOP), and overall positioning deviation. Through comparative analyses between deciduous and coniferous stands, the study reported horizontal positional deviations ranging from approximately 1.2 m to 2.0 m, depending on forest type, and noted that GNSS performance degrades under dense canopy conditions. The findings underscore the importance of considering environmental attenuation effects and DOP variations when assessing kinematic GNSS accuracy, particularly for off-road navigation and vehicle guidance applications where multipath and signal blockage are prevalent.

Despite advancements in GNSS technology, several challenges persist in performance evaluation. One significant issue is the variability of performance metrics based on environmental conditions. For example, urban canyons can severely degrade GNSS signal quality, leading to increased positioning errors. Therefore, performance evaluations must consider diverse scenarios to provide a comprehensive understanding of GNSS capabilities [12].

2 GNSS Data Collection

GNSS 5-click receiver (U-blox NEO-M8N) along with U blox Multi-band Antenna were used to collect data of 3 Feb 2024 (24 hours data for static observation) and local afternoon of 4 Feb 2024 (kinematic observation) in Melaka, Malaysia as shown in Fig. 1. U-blox NEO-M8N GNSS receiver module was used to collect the static and kinematic observations of BeiDou/GPS/GLONASS/Galileo at a sampling interval of one second with the U-center software, developed by U-blox. Tab. 1 shows the main specifications for the U-blox NEO-M8N GNSS module.

The U-center software, developed by U-blox, is a comprehensive platform designed for real-time evaluation, configuration, and analysis of GNSS receiver performance. It provides an integrated graphical interface that enables users to visualize satellite tracking, assess positioning quality, and configure receiver parameters with high flexibility. The software supports the decoding of both standard NMEA and proprietary UBX protocols, allowing detailed inspection of navigation and timing data. Real-time visualization features include sky plots for satellite geometry, signal-to-noise ratio (SNR) bar graphs, and trajectory maps that depict receiver motion in both static and kinematic conditions.

Tab. 1 Main specifications for the U-blox NEO-M8N GNSS module

Parameter	**Specification**
GNSS Constellations Supported	GPS L1C/A, SBAS L1C/A, QZSS L1C/A, QZSS L1 SAIF, GLONASS L1OF, BeiDou B1I, Galileo E1B/C
Navigation Sensitivity	167 dBm
Update Rate	Up to 5 Hz
Horizontal Position Accuracy	~2.5 m (2D)

The static observation was conducted at a fixed open-area location, where GNSS data were continuously recorded for a 24-hour period on 3 February 2024. This duration allows the receiver to collect data from all GNSS satellites at different times of the day, helping to account for any temporal variations in the satellite signals. The kinematic experiment was done in a complex observation scenario with the GNSS observations for about 23 min (12:15:06–12:38:05 UTC+8) along One Krubong Lake, Melaka.

The evaluation process begins by analyzing data collected from GNSS devices in the form of scatter plots and time series plots. Scatter plots help visualize the distribution of data points, while time series plots provide insights into how the GNSS systems perform over time. To quantify the variability in performance, several key metrics are calculated. These include the standard deviation, which measures how spread out the data is, the difference between the maximum and minimum values, and the average value. These metrics provide a clear picture of the consistency and stability of the GNSS configurations.

The ultimate goal of this evaluation is to determine which GNSS system offers the best location service performance in Malaysia. By comparing the calculated metrics across different GNSS configurations, researchers can make informed decisions about which system is most suitable for various applications in the Malaysian context.

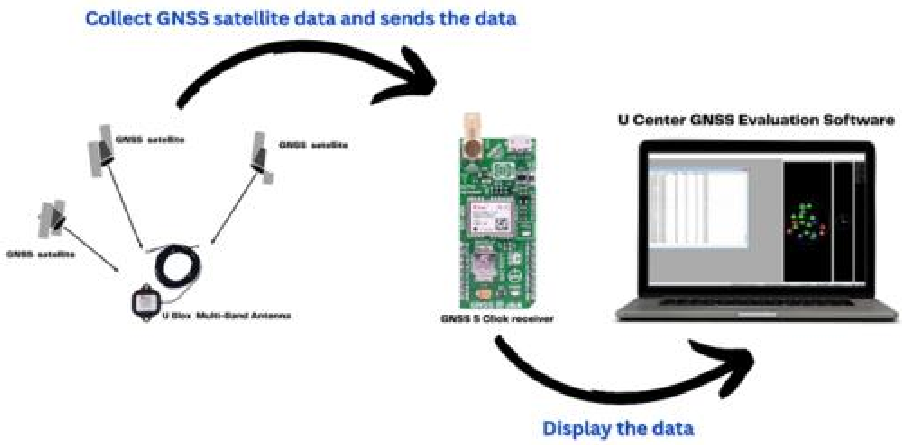

Fig. 1 Data collection process

2.1 Position Accuracy Computation for Static Application

The positional accuracy of the GNSS observations was evaluated through statistical and Root Mean Square (*RMS*) analyses in both geodetic and Cartesian coordinate domains. The latitude (ϕ), longitude (λ), and altitude (h) values were first processed to determine their mean and standard deviation. These parameters represent the central location and dispersion of the receiver's position solutions.

The mean position for each coordinate component was computed as:

$$\bar{X} = \frac{1}{N}\sum_{i=1}^{N} X_i \qquad (1)$$

where X_i denotes the individual coordinate measurement (either ϕ_i, λ_i *or* h_i), and N is the total number of samples.

The standard deviation (λ_i) quantifies the spread of the position estimates relative to the mean value and was calculated using:

$$\sigma_X = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(X_i - \bar{X}\right)^2} \tag{2}$$

The standard deviations of latitude and longitude, originally expressed in angular units (degrees), were converted to metric units (meters) using the mean Earth radius, R_e = 6 371 km. The conversion formulas are given by:

$$\sigma_{\phi_m} = \sigma_\phi \frac{\pi}{180} R_e \tag{3}$$

$$\sigma_{\lambda_m} = \sigma_\lambda \frac{\pi}{180} R_e \cos\left(\bar{\phi}\right) \tag{4}$$

where σ_ϕ and σ_λ denote the angular standard deviations of latitude and longitude, respectively, and ϕ is the mean latitude. The cosine term compensates for the longitudinal convergence effect with increasing latitude.

The horizontal accuracy was expressed as the two-dimensional *RMS* error, which combines the standard deviations of latitude and longitude in meters:

$$RMS_{2D} = \sqrt{\sigma_{\phi_m}^2 + \sigma_{\lambda_m}^2} \tag{5}$$

To evaluate the overall spatial accuracy, the three-dimensional *RMS* error was computed from the standard deviations of the Cartesian coordinates (*x, y, z*) in the Earth-Centered, Earth-Fixed (ECEF) reference frame:

$$RMS_{3D} = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2} \tag{6}$$

3 Results and Discussion

In this section, the focus is on evaluating the performance of the GNSS positioning services in Malaysia. The primary goal is to assess and discuss how various GNSS configurations fare in terms of accuracy and reliability. This evaluation is carried out using both static and kinematic observations.

3.1 Static Observation Analysis

The location service performance for multiple GNSS systems such as GPS, GLONASS, BeiDou, Galileo, combination of GPS and GLONASS (GPS + GLONASS), combination of GPS and BeiDou (GPS + BeiDou) and combination of GPS and BeiDou (GPS + Galileo) is evaluated based on the analysis of latitude and longitude, altitude and Root Mean Square for 2D and 3D in static manner.

Figs 2–8 show the position scatter plot (latitude vs longitude) of the 7 GNSS positioning configurations, visually representing the spatial distribution of coordinates from different satellite navigation systems. Each figure shows the variation in point dispersion in the horizontal plane among these configurations, each conveying a unique level of precision. The most striking observation emerges with the GPS + BeiDou configuration. The points in this dataset are tightly clustered, indicating a minimal spread and, thereby, the highest precision. This setup stands out as the optimal choice for static positioning service performance due to its accuracy, represented by the lowest standard deviation as shown in Tab. 2. Comparing the spatial distribution of points on these position scatter plots, it unveils valuable insights into the precision and reliability of different satellite navigation systems. It becomes evident that the GPS + BeiDou configuration offers the most consistent and accurate results, making it the top choice for applications where precision in location services is paramount.

Tab. 2 Comparison of standard deviation of latitude and longitude coordinates for multiple GNSS configurations (standard deviation values are in meters)

Parameters	GPS	GLONASS	BeiDou	Galileo	GPS + GLONASS	GPS + BeiDou	GPS+ GELILEO
latitude (std)	1.1110	4.0431	2.2102	2.3970	1.8302	1.2122	2.1454
longitude (std)	1.5276	6.4249	1.8243	3.5461	2.5496	1.0714	1.8043

A key aspect of the evaluation process involves the consideration of altitude as a critical parameter in assessing location service performance. Altitude, in this context, refers to the vertical height of an object or point in relation to sea level or ground level. It is an essential factor as it can have a substantial impact on the accuracy and efficiency of location-based services. The fluctuation of altitude measurements over time is depicted through graphical representations, with low fluctuation signifying stability and high fluctuation indicating variability in altitude data.

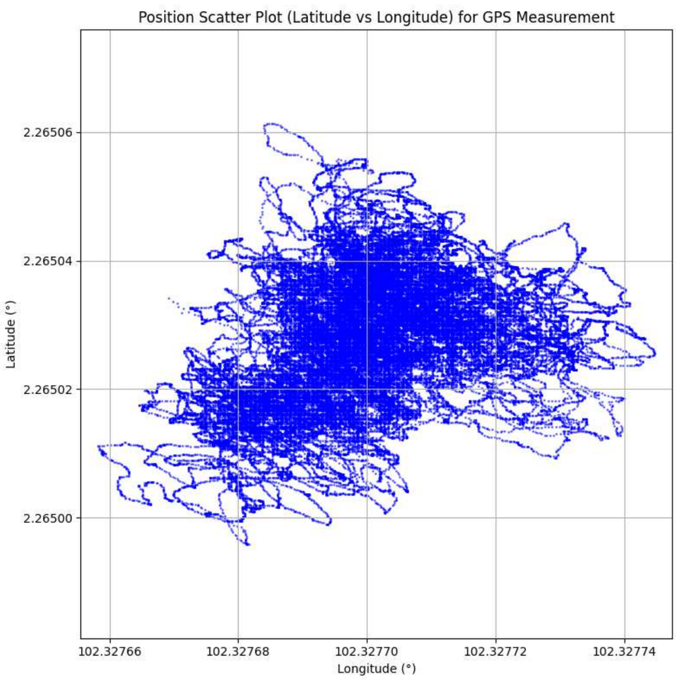

Fig. 2 Position scatter plot (latitude vs longitude) of GPS configuration

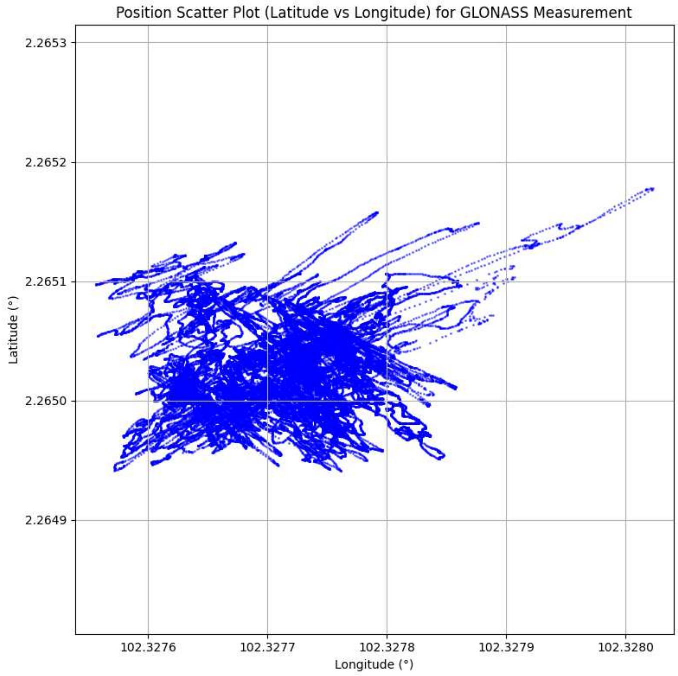

Fig. 3 Position scatter plot (latitude vs longitude) of GLONASS configuration

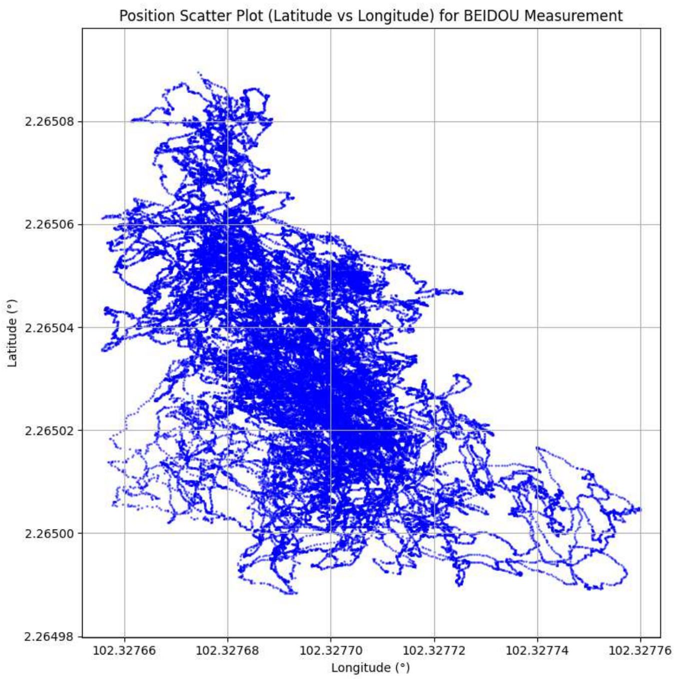

Fig. 4 Position scatter plot (latitude vs longitude) of BeiDou configuration

DOI 10.3849/aimt.01913

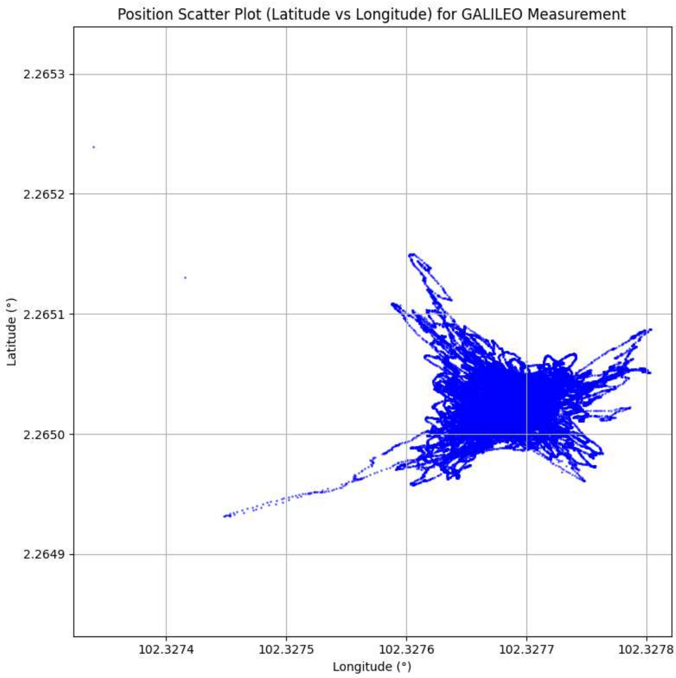

Fig. 5 Position scatter plot (latitude vs longitude) of Galileo configuration

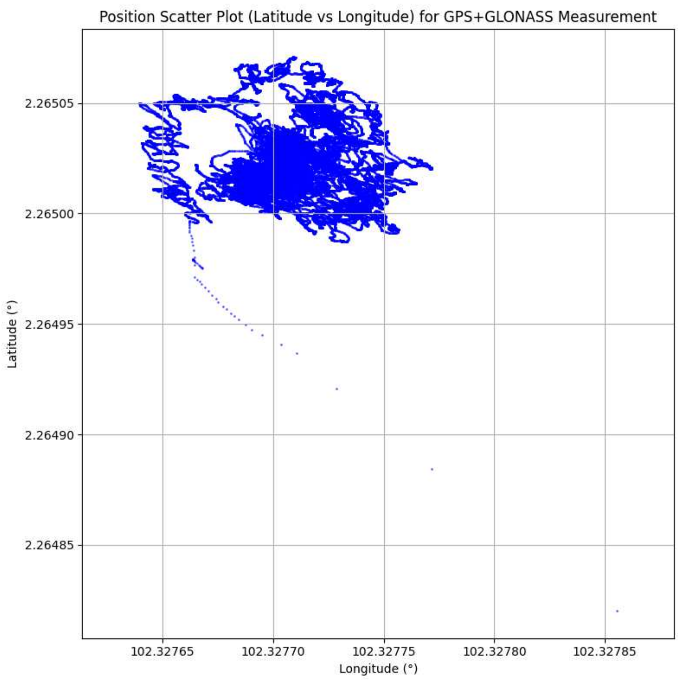

Fig. 6 Position scatter plot (latitude vs longitude) of GPS + GLONASS configuration

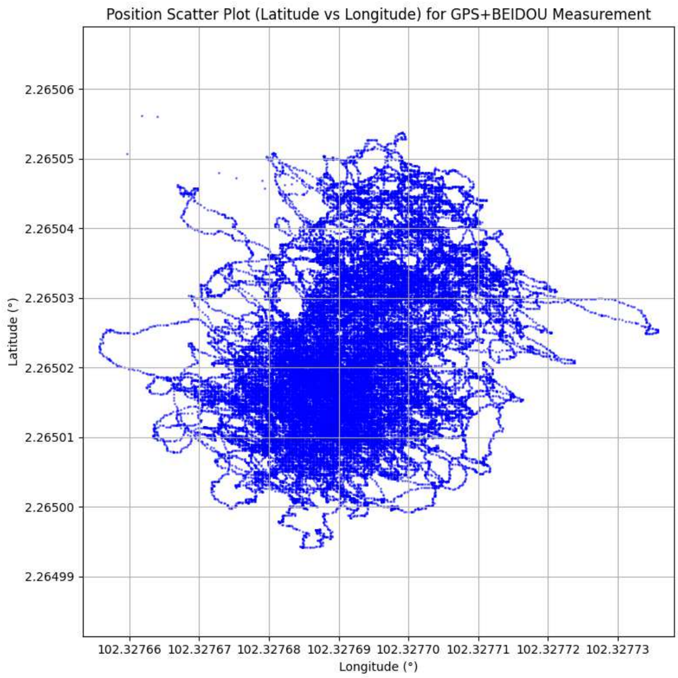

Fig. 7 Position scatter plot (latitude vs longitude) of GPS + BeiDou configuration

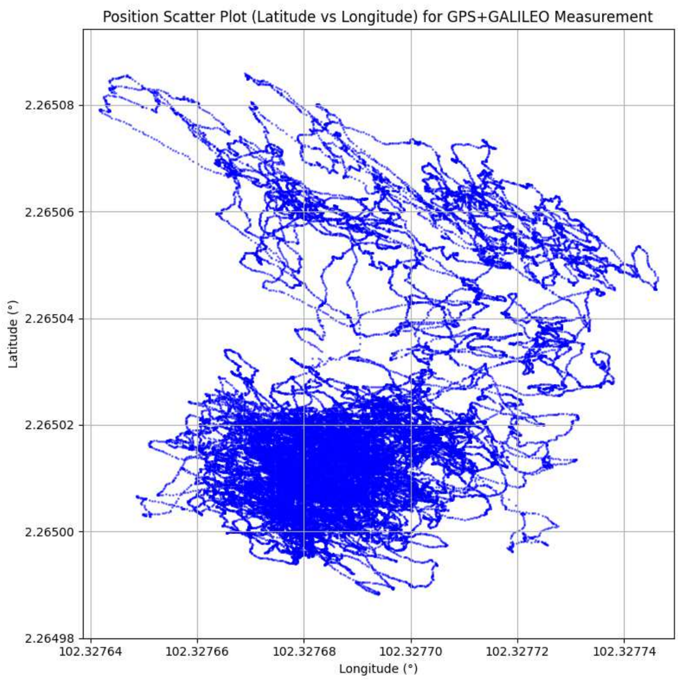

Fig. 8 Position scatter plot (latitude vs longitude) of GPS + Galileo configuration

Figs 9–15 show the 24 hours' time series plot of altitude for the 7 configurations. It is evident that the GPS + BeiDou configuration consistently provides the most stable altitude measurements, showcasing minimal fluctuation over time. This stability is a crucial factor in ensuring the reliability and accuracy of positioning services, particularly in scenarios where precise vertical positioning is essential. In contrast, the GLONASS configuration displays the highest variability in altitude measurements, signifying that it may not be as dependable when it comes to maintaining consistent altitude data. This fluctuation can introduce uncertainties in applications that demand reliable vertical positioning information.

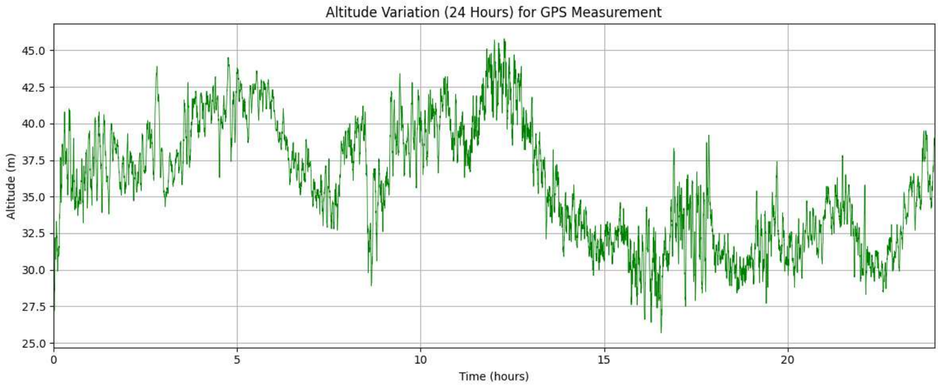

Fig. 9 24 hours' *time series plot of altitude for GPS-only configuration*

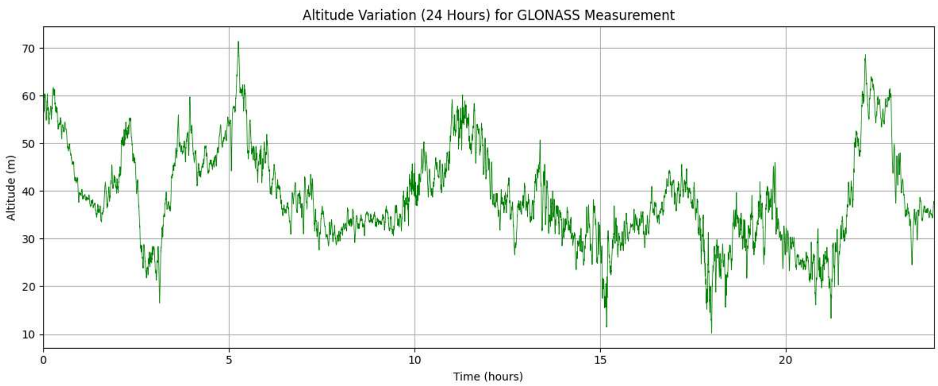

Fig. 10 24 hours' *time series plot of altitude for GLONASS-only configuration*

Tab. 3 shows a comparative analysis of 7 satellite navigation system configurations based on "Altitude (std)" where "std" represents the standard deviation. The parameter is key for assessing the accuracy and stability of altitude measurements. The data reveals that the GPS + BeiDou configuration consistently outperforms other configurations, signifies the least altitude variation, and the lowest standard deviation, indicating the most stable and consistent altitude measurements. In contrast, the GLONASS-only configuration exhibits the highest standard deviation, indicating less stable and accurate altitude data. These findings emphasize that GPS + BeiDou is the optimal choice for applications where precise and stable altitude measurements are critical, such as aviation and geodetic surveys.

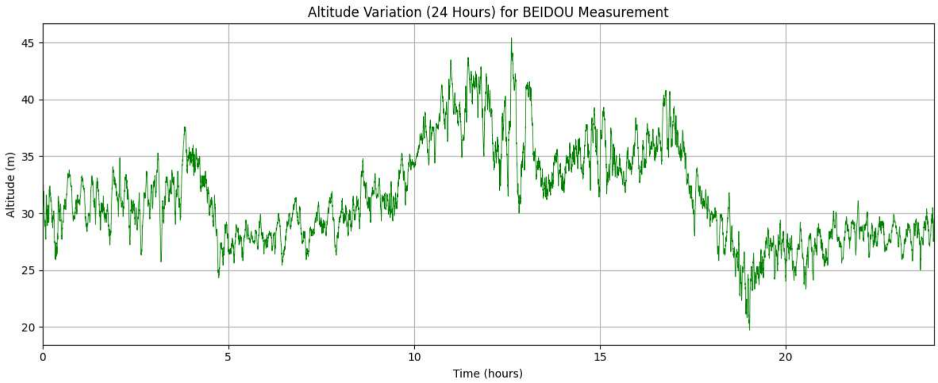

Fig. 11 24 hours' *time series plot of altitude for BeiDou-only configuration*

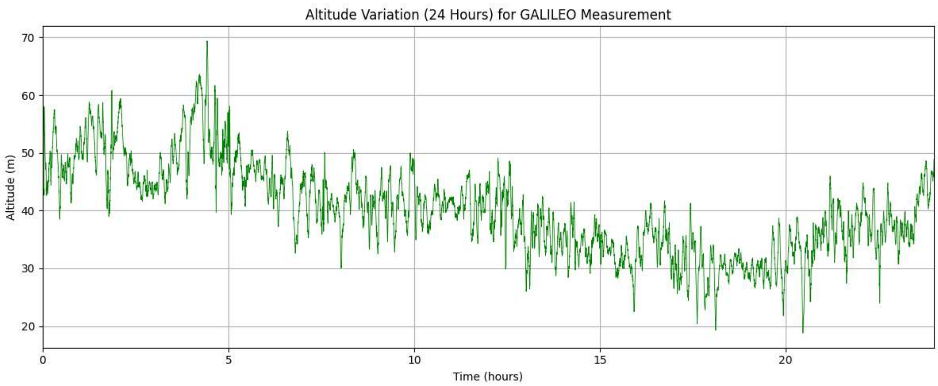

Fig. 12 24 hours' *time series plot of altitude for Galileo-only configuration*

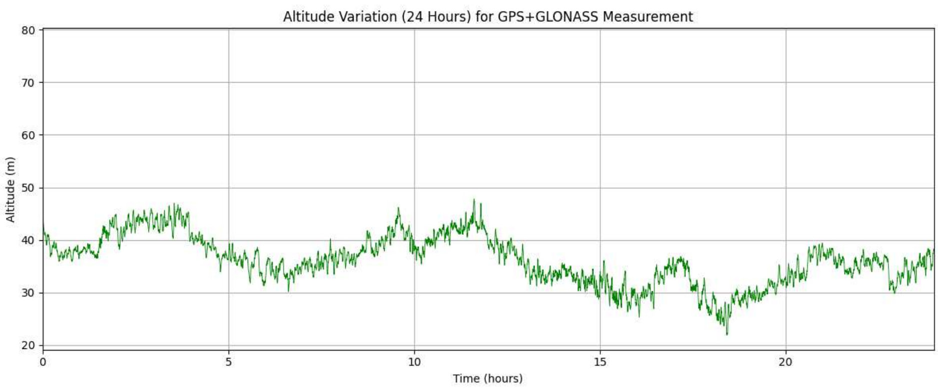

Fig. 13 24 hours' *time series plot of altitude for GPS + GLONASS configuration*

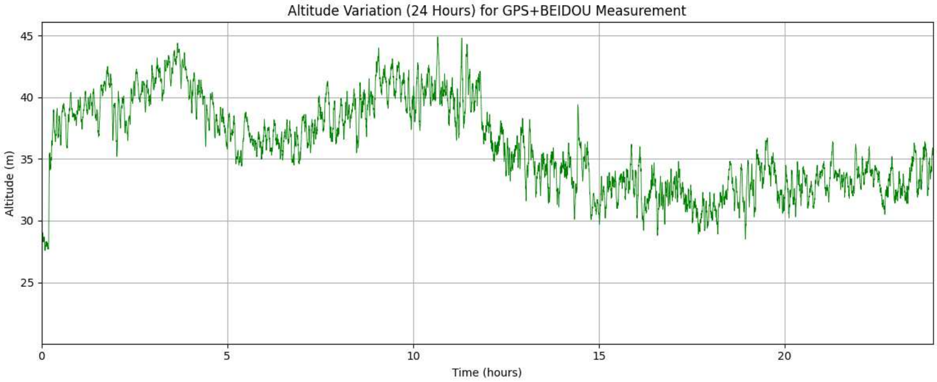

Fig. 14 24 hours' *time series plot of altitude for GPS + BeiDou configuration*

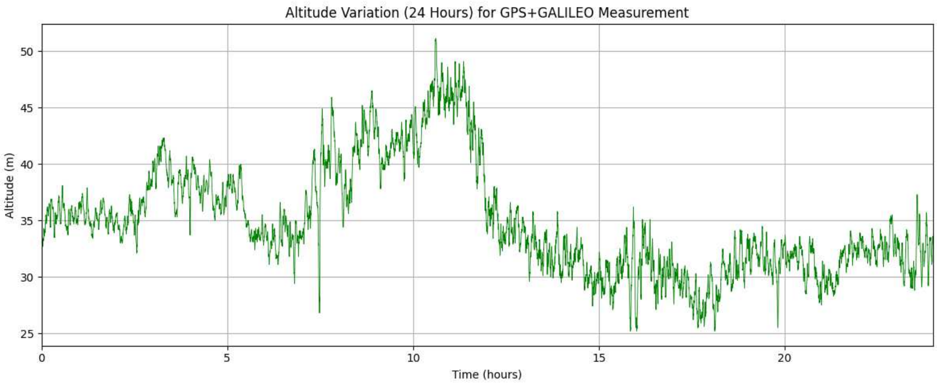

Fig. 15 24 hours' *time series plot of altitude for GPS + Galileo configuration*

Tab. 3 Comparison of standard deviation of Altitude for multiple GNSS configurations (standard deviation values are in meters)

Parameters	GPS	GLONASS	BeiDou	Galileo	GPS + GLONASS	GPS + BeiDou	GPS + Galileo
Altitude (std)	4.0622	9.9205	4.2224	7.8594	4.5832	3.5937	4.8440

Tab. 4 summarizes the 2D and 3D RMS positioning accuracies obtained from different GNSS constellations and their combinations. In general, the multi-GNSS configurations demonstrate superior positioning performance compared to the single-constellation systems. Among the standalone constellations, GPS achieves the highest accuracy, with 2D and 3D RMS errors of 1.8889 m and 4.4790 m, respectively. Conversely, GLONASS exhibits the lowest positioning performance, recording RMS errors of 7.5912 m (2D) and 12.4882 m (3D). The reduced accuracy of GLONASS may be attributed to less favorable satellite geometry and higher observation noise characteristics.

Tab. 4 Comparison of 2D and 3D RMS accuracy for multiple GNSS configurations (RMS values are in meters)

Parameters	GPS	GLONASS	BeiDou	Galileo	GPS + GLONASS	GPS + BeiDou	GPS + Galileo
RMS_{2D}	1.8889	7.5912	2.8659	4.2803	3.1385	1.6178	2.8033
RMS_{3D}	4.4790	12.4882	5.0985	8.9473	5.5528	3.9393	5.5927

Integration of multiple constellations significantly enhances positioning accuracy due to improved satellite availability and geometric diversity. The GPS + BeiDou combination yields the best overall results, achieving the lowest RMS errors of 1.6178 m (2D) and 3.9393 m (3D). This improvement suggests that the complementary spatial distribution between GPS and BeiDou satellites effectively reduces geometric dilution of precision and enhances solution robustness. The GPS + GLONASS and GPS + Galileo combinations also exhibit accuracy improvements relative to their respective single-constellation counterparts, though the magnitude of enhancement is comparatively smaller.

As expected, the 3D RMS values are consistently higher than their 2D counterparts for all configurations, reflecting the inherent limitations in vertical positioning accuracy caused by weaker satellite geometry and atmospheric delay effects in the elevation domain. Overall, the results confirm that multi-GNSS integration provides a substantial benefit in positioning accuracy, with the GPS + BeiDou configuration demonstrating the most favorable performance in this study.

3.2 Kinematic Analysis

The kinematic experiment was done in a complex observation scenario. As shown in Fig.16, the experimenter held to collect the GNSS observations for about 23 min along One Krubong Lake Garden in the counterclockwise direction. The blue dotted line represents the approximate walking trajectory. The lakeside path is mostly covered by trees, which is a challenging environment for GNSS positioning. The experimenter passed through one dense forest area, and the rest is semi-open spaces interlaced with fully sheltered environments. During the process of kinematic data collection, the vegetation canopy can block satellite signals, resulting in signal attenuation or loss of lock, and may cause complicated multipath effects. Furthermore, the huge lake is also a potential source of multipath interference.

The performance of various GNSS systems, including GPS, GLONASS, BeiDou, Galileo – and their combinations (GPS + GLONASS, GPS + BeiDou, GPS + Galileo) are evaluated using a kinematic approach, focusing on the analysis of latitude and longitude coordinates.

In the kinematic data collection process, altitude is excluded from consideration. The kinematic positioning performance of the GNSS receiver was evaluated using the recorded latitude and longitude coordinates at a sampling interval of 1 Hz. The positional dispersion of the trajectory was visualized through a latitude–longitude scatter plot, which represents the spatial consistency of the receiver's position estimates during motion. The plot exhibits the distribution of instantaneous positions over the observation period, allowing qualitative assessment of tracking stability and positional spread.

In addition to the spatial analysis, the precision of satellite geometry was assessed using the Dilution of Precision (DOP) indicators, namely the Horizontal DOP

(HDOP), Vertical DOP (VDOP), and Position DOP (PDOP). These parameters quantify the amplification of range measurement errors due to satellite geometry. Lower DOP values correspond to more favorable satellite configurations and, consequently, higher positioning accuracy. The temporal variation of HDOP, VDOP, and PDOP was analyzed to evaluate the stability of satellite geometry throughout the kinematic session. The results show that the DOP values remained within acceptable operational limits, indicating consistent satellite visibility and geometry during data acquisition.

Overall, the combination of the spatial scatter plot and DOP analysis provides a comprehensive assessment of the GPS receiver's kinematic performance. The latitude-longitude scatter illustrates the positional repeatability, while the DOP metrics substantiate the reliability of the observed satellite geometry over time.

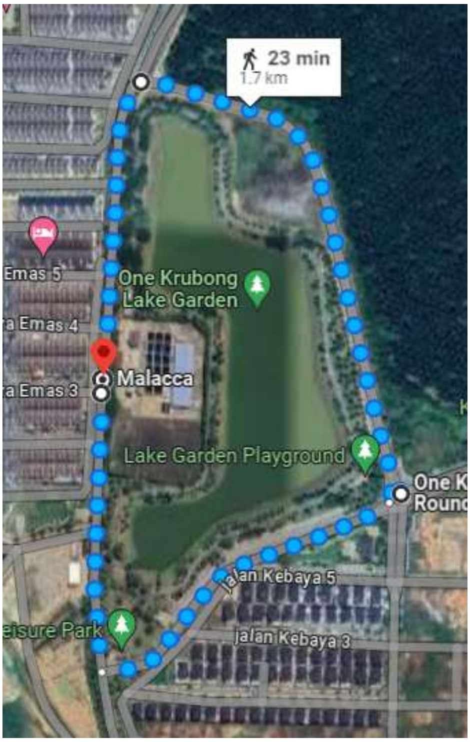

Fig. 16 Locations for kinematic GNSS data collection and their surrounding environments

Figs 17–23 show the position scatter plot (latitude vs longitude) of the 7 GNSS positioning configurations, visually representing the spatial distribution of coordinates from different satellite navigation systems. The positioning results of the GPS + BeiDou are the lowest PDOP values and follow the motion trajectory well. GPS performs best among the three systems, following BeiDou is a bit inferior to GPS, especially in dense forest areas. Galileo has the worst performance, with the highest PDOP values.

Tab. 5 presents a comparative evaluation of the average DOP parameters – HDOP, VDOP, and PDOP – for individual GNSS and their combined configurations. The results demonstrate that multi-constellation integration significantly enhances geometric strength compared to the use of a single GNSS

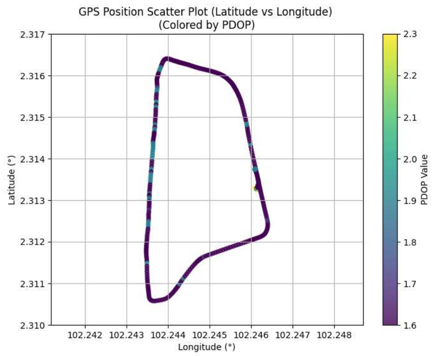

Fig. 17 Position scatter plot (latitude vs longitude) of GPS configuration conducted in a kinematic manner

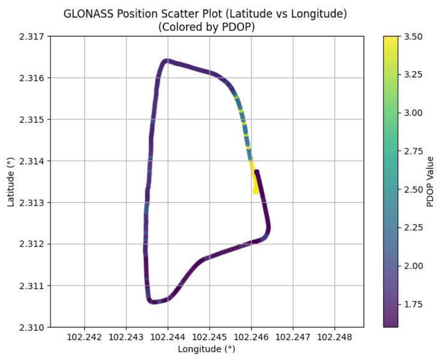

Fig. 18 Position scatter plot (latitude vs longitude) of GLONASS configuration conducted in kinematic manner

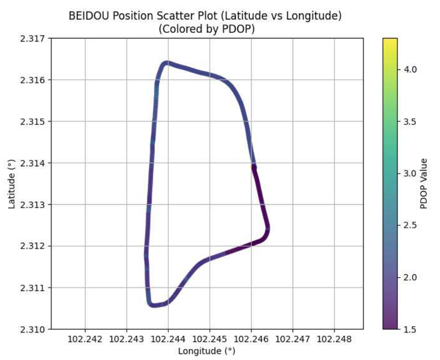

Fig. 19 Position scatter plot (latitude vs longitude) of BeiDou configuration conducted in a kinematic manner

 DOI 10.3849/aimt.01913

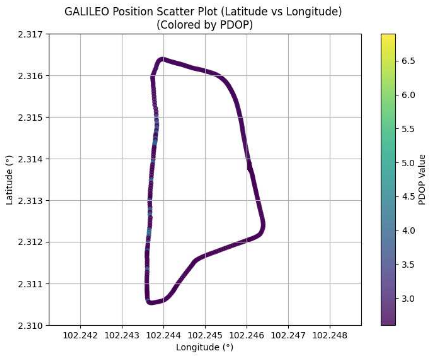

Fig. 20 Position scatter plot (latitude vs longitude) of Galileo configuration conducted in a kinematic manner

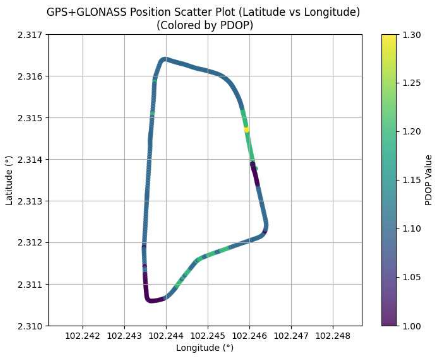

Fig. 21 Position scatter plot (latitude vs longitude) of GPS + GLONASS configuration conducted in a kinematic manner

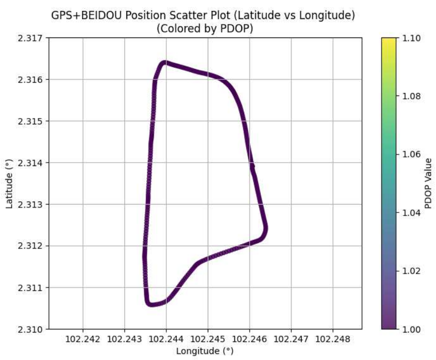

Fig. 22 Position scatter plot (latitude vs longitude) of GPS + BeiDou configuration conducted in a kinematic manner

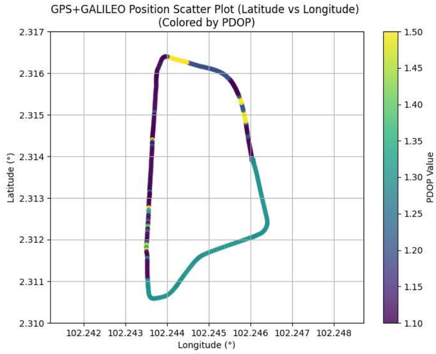

Fig. 23 Position scatter plot (latitude vs longitude) of GPS + Galileo configuration conducted in a kinematic manner

Tab. 5 Comparison of average value of HDOP, VDOP, and PDOP for multiple GNSS configurations

Parameters	GPS	GLONASS	BeiDou	Galileo	GPS + GLONASS	GPS + BeiDou	GPS + Galileo
HDOP (average)	0.9766	1.1143	0.9658	1.7163	0.6442	0.6000	0.6545
VDOP (average)	1.4536	1.7245	1.7313	2.6998	0.8892	0.8005	1.0265
PDOP (average)	1.7304	2.0882	2.0104	3.1800	1.1120	1.0005	1.2289

Among the individual constellations, the BeiDou system exhibits the lowest average HDOP (0.9658) and a comparable PDOP (2.0104) relative to GPS (1.7304), indicating a favorable satellite geometry in the observed region. However, Galileo shows comparatively higher DOP values across all metrics, particularly a VDOP of 2.6998 and a PDOP of 3.1800, suggesting less optimal satellite geometry during the test interval.

The benefits of multi-constellation integration are clearly observed. The GPS + BeiDou combination achieves the lowest overall DOP values, with HDOP = 0.6000, VDOP = 0.8005, and PDOP = 1.0005, reflecting substantial improvement in positional geometry. Similarly, GPS + GLONASS and GPS + Galileo also exhibit improved performance compared to their single-system counterparts, though to a slightly lesser extent. The reduction in DOP values for combined systems confirms the advantage of multi-GNSS integration in mitigating satellite geometry limitations, thereby enhancing positioning accuracy and reliability under kinematic conditions.

4 Conclusion

The evaluation of GNSS positioning performance in Malaysia, conducted under both static and kinematic observation modes, indicates that the combined GPS and BeiDou

(GPS + BeiDou) configuration provides superior overall performance. The integration of these two constellations significantly increases satellite availability, thereby improving positional accuracy and solution reliability.

Comprehensive analyses were performed using positional scatter plots in the horizontal plane (latitude – longitude domain), which clearly demonstrated that the GPS + BeiDou combination yielded a tighter clustering of position estimates compared to other configurations. Further examination of the DOP parameters – specifically the VDOP, HDOP, and PDOP – corroborated these findings. The GPS + BeiDou configuration consistently exhibited lower average DOP values, indicating a stronger satellite geometry and reduced sensitivity to measurement errors, particularly in the vertical component.

Overall, the GPS + BeiDou integration demonstrates substantial potential for enhancing GNSS-based positioning accuracy and robustness within the Malaysian region. This improvement is especially relevant to applications in navigation, asset tracking, geospatial surveying, and telecommunications. Future research could extend this investigation by incorporating additional constellations such as QZSS, and NavIC, thereby providing a more comprehensive global assessment of multi-GNSS performance and interoperability.

Acknowledgement

The authors wish to acknowledge the Universiti Teknikal Malaysia Melaka (UTeM) for providing the research platforms and facilities.

References

[1] ANYAEGBU, E. and P. HANSEN. GNSS Performance Evaluation for Deep Urban Environments using GNSS Foresight. In: *Proceedings of the 35th International Technical Meeting of the Satellite Division of the Institute of Navigation*. Denver: ION, 2022, pp. 1127-1136. DOI 10.33012/2022.18468.

[2] ZHU, L. et al. GNSS Timing Performance Assessment and Results Analysis. *Sensors,* 2022, **22**(7), 2486. DOI 10.3390/s22072486.

[3] SWAMINATHAN, H.B., A. SOMMER, A. BECKER and M. ATZMUELLER. Performance Evaluation of GNSS Position Augmentation Methods for Autonomous Vehicles in Urban Environments. *Sensors,* 2022, **22**(21), 8419. DOI 10.3390/s22218419.

[4] HAMZA, V., B. STOPAR, T. AMBROŽIČ and O. STERLE. Performance Evaluation of Low-Cost Multi-Frequency GNSS Receivers and Antennas for Displacement Detection. *Applied Sciences,* 2021, **11**(14), 6666. DOI 10.3390/app11146666.

[5] WANG, Y., F.-P. SUN and X. WANG. Defensive Performance Evaluation Methods of the GNSS for Satellite Navigation Countermeasures. *IEEE Access,* 2024, **12**, pp. 51719-51739. DOI 10.1109/ACCESS.2024.3373057.

[6] KUBO, N. GNSS Applications and QZSS High-Accuracy Services. In*: UTOKYO/ICG Training on Global Navigation Satellite Systems (GNSS).* Lalitpur: GNSS, 2024.

[7] CAI, B., B. WU and D. LU. Survey of Performance Evaluation Standardization and Research Methods on GNSS-Based Localization for Railways. *Chinese Journal of Electronics,* 2020, **29**(1), pp. 22-33. DOI 10.1049/cje.2019.09.003.

[8] SULAIMAN, M.S.A., C.Z. YONG and O. ZAINON. Global Positioning System Performance Assessment with Precise Point Positioning and Relative Positioning. *Journal of Advanced Geospatial Science & Technology,* 2022, **2**(1), pp. 49-66.

[9] PISHEHVARI, A., U. IURGEL, M. STEFER and B. TIBKEN. Range-Doppler Registration. In: *Proceedings of the 5th International Conference on Control and Robotics Engineering (ICCRE)*. Osaka: IEEE, 2020, pp. 169-176. DOI 10.1109/ICCRE49379.2020.9096494.

[10] NG, K.M., J. JOHARI, S.A.C. ABDULLAH, A. AHMAD and B.N. LAJA. Performance Evaluation of the RTK-GNSS Navigating under Different Landscape. In: *Proceedings of the 18th International Conference on Control, Automation and Systems (ICCAS)*. PyeongChang: IEEE, 2018, pp. 1424-1428.

[11] RYBANSKÝ, M., et al. GNSS Signal Quality in Forest Stands for Off-Road Vehicle Navigation. *Applied Sciences,* 2023, **13**(10), 6142. DOI 10.3390/app13106142.

[12] MURPHY, T. and T. IMRICH. Implementation and Operational Use of Ground-Based Augmentation Systems (GBASs) – A Component of the Future Air Traffic Management System. *Proceedings of the IEEE,* 2008, **96**(12), pp. 1936-1957. DOI 10.1109/JPROC.2008.2006101.