Raufu IO (2025)
Nova Geodesia 5(2):336
Research Article

Exploring the accuracy of height measurements with multi-constellation RTK GNSS

Ibrahim O. RAUFU

Lead City University, School of Environmental Design and Management, Ibadan, Oyo State, Nigeria; raufuibrahimolatunji@gmail.com

Abstract

Accurate height determination is crucial in various geospatial applications, and Real-Time Kinematic (RTK) GNSS plays a key role in providing high-precision positioning. This study explores the accuracy of multi-constellation RTK GNSS height measurements by comparing them with ground truth static data collected over different observation periods (2-hour, 1-hour, and 30-minute sessions). Three RTK configurations: GPS-only, GPS + GLONASS + Galileo, and a full GNSS solution (GPS + GLONASS + Galileo + BeiDou), were assessed to determine their relative performance in height estimation. The results indicate that longer observation durations improve accuracy, with the 2-hr session yielding the smallest errors across all configurations. Multi-constellation solutions generally outperformed GPS-only configurations, providing more stable height measurements, although the GNSS RTK configuration exhibited the largest variations in the 30-minute session. A one-way ANOVA analysis at a 95% confidence level confirmed that the variations between different RTK configurations were statistically insignificant, implying that all solutions exhibit similar uncertainties. These findings emphasize the benefits of integrating multiple satellite constellations for RTK positioning while also highlighting the importance of observation duration and site-specific factors in height determination.

Keywords: ANOVA; GPS; height accuracy; multi-constellation; RTK GNSS; static observation

Introduction

The advent of Global Navigation Satellite Systems (GNSS) has transformed positioning, navigation, and timing applications across industries, including surveying, construction, agriculture, and transportation (Isioye *et al.*, 2018; Tata *et al.*, 2020; Abubakar and Hermann, 2021). Among the high-precision GNSS techniques, Real-Time Kinematic (RTK) GNSS has garnered considerable attention for its ability to provide centimeter-level accuracy in real-time applications (Odijk, 2017; Tidey and Odolinski, 2023). RTK GNSS involves a base station with a known fixed position transmitting correction signals to a rover receiver, enabling precise relative positioning (Pirti *et al.*, 2013; Langley *et al.*, 2017; Allahyari *et al.*, 2018).

Traditional RTK operations predominantly relied on single-constellation systems, particularly the U.S. Global Positioning System (GPS), which required at least five visible satellites to resolve positional unknowns and initiate surveys (El-Rabbany, 2006; Pirti *et al.*, 2013). However, achieving adequate satellite visibility in

Received: 12 Mar 2025. Received in revised form: 22 Apr 2025. Accepted: 23 Apr 2025. Published online: 23 Apr 2025.

challenging environments such as urban canyons, dense forests, or mountainous regions remained problematic. To address this limitation, additional constellations such as Russia's GLONASS, China's BeiDou (BDS), Europe's Galileo, and Japan's Quasi-Zenith Satellite System (QZSS) has emerged as a viable solution for enhancing satellite availability, positional accuracy, and system reliability (Odolinski and Teunissen, 2019; Thom *et al.*, 2019).

The multi-constellation approach enhances performance by improving satellite geometry, offering increased redundancy, and reducing the impact of signal obstructions. Studies have demonstrated the advantages of integrating multiple constellations in RTK applications. For example, Odolinski and Denys (2015) and Odolinski et al. (2015) showed that combining QZSS with GPS, Galileo, and BDS allowed the use of a higher elevation cut-off angle while maintaining millimeter-level accuracy in single-epoch RTK mode. Similarly, Xi et al. (2018) reported that adding BeiDou to GPS enhanced positioning precision by 20-30%. In a comparative field test, Omer et al. (2022) evaluated different GNSS constellation combinations and found that multi-constellation RTK significantly improved horizontal and vertical accuracy over varying baseline lengths.

Height determination is a critical component of GNSS applications, particularly in surveying, geodesy, and civil engineering (Gillins and Eddy, 2016; Raufu and Tata, 2022). Accurate height measurements are essential for applications such as construction projects, flood modelling, tectonic deformation studies, and infrastructure development. However, achieving high accuracy in height determination is challenging due to error sources such as atmospheric delays, satellite geometry, and multipath effects (Krzyzek and Kudrys, 2022). The integration of multiple satellite constellations in RTK GNSS has the potential to enhance height accuracy by improving satellite geometry and mitigating these errors.

Despite the advancements in GNSS technology, research on the performance of multi-constellation RTK GNSS specifically for height accuracy remains limited. While existing studies have extensively evaluated horizontal positioning accuracy, fewer have focused on the comparative analysis of height accuracy, particularly under diverse environmental conditions. Notably, Weaver et al. (2018) found that combining GPS and GLONASS improved ellipsoid height accuracy by 19% and horizontal accuracy by 7%, demonstrating the potential benefits of multi-constellation systems. However, Martin and McGovern (2012) observed no significant improvement in height accuracy when GLONASS was added to GPS in network RTK operations in Ireland. These mixed results highlight the need for further investigation of how different GNSS configurations impact height measurement accuracy.

This study aims to address this gap by systematically evaluating the height accuracy achievable with three distinct GNSS configurations: GPS-only, GPS + GLONASS + Galileo, and GPS + GLONASS + Galileo + BeiDou. The research involves comparing RTK-derived height measurements with high-precision reference values obtained through static GNSS observations. By analyzing the performance of these multi-constellation setups, this study seeks to provide valuable insights into the suitability of different GNSS configurations for height determination across varying environmental conditions.

Materials and Methods

Description of the study area

The study area for this research is the Federal University of Technology Akure (FUTA), situated in Akure South Local Government Area, Ondo State, Nigeria. The geographic coordinates of the area extend from latitude 7°18' N to 7°40' N and longitude 5°07'20" E to 5°08'40" E (Figure 1), with an average elevation of 390 meters above mean sea level (Raufu *et al.*, 2023). Spanning approximately 577.97 hectares, the university's landscape is characterized by varied topography, including flat lands, gentle slopes, and undulating terrain. The twenty (20) control points used for the observations are all located within the FUTA campus in Akure South Local Government Area (Figure 2).

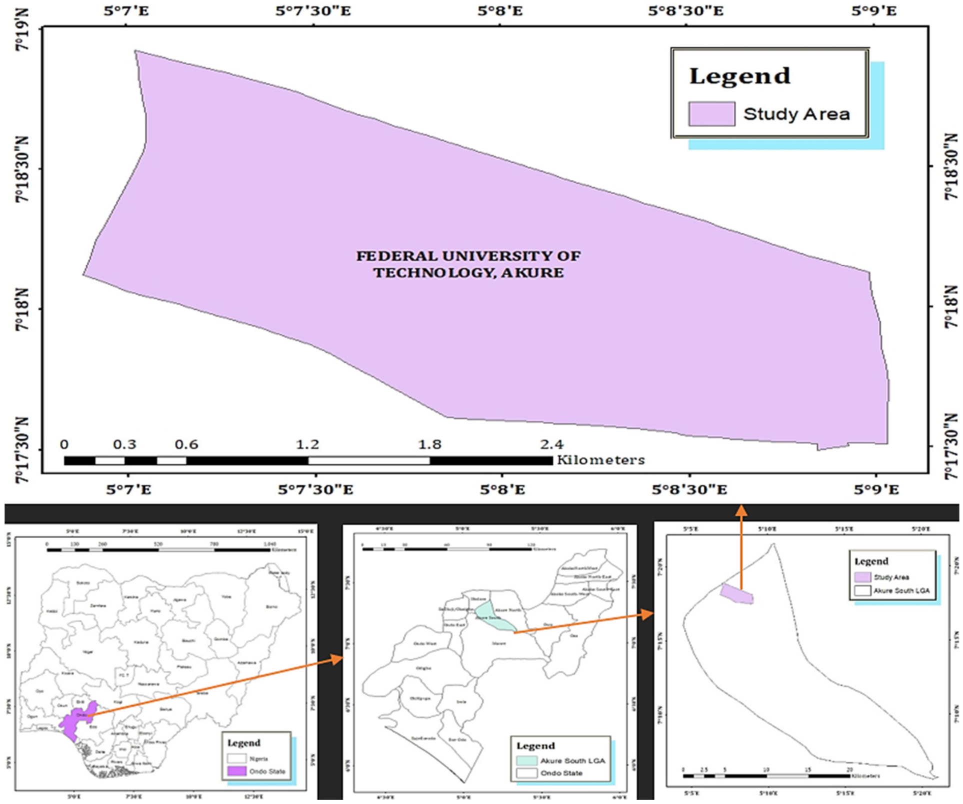

Figure 1. Map of the study area

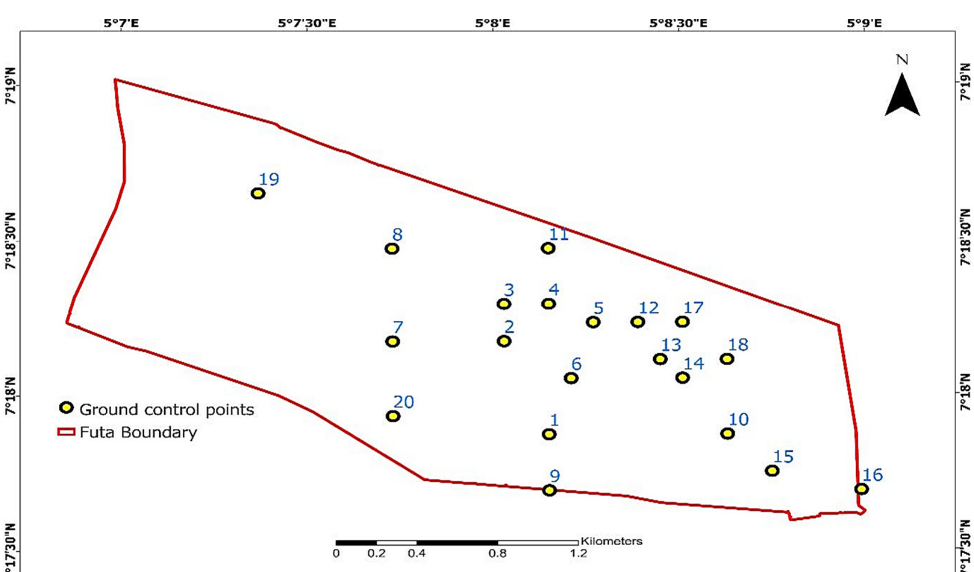

Figure 2. Distribution of control points in the study area

Method

The methodology employed in this study consists of three main stages. First, three-dimensional positioning for the twenty (20) control points within the study area was established using the static GNSS positioning method. This involved utilizing South Differential GNSS receivers, with observation sessions conducted for durations of 2 hours, 1 hour, and 30 minutes. Second, the GNSS receivers were used to observe the control points in RTK mode for 180 seconds at each point, applying different combinations of satellite constellations to obtain the XYZ coordinate values. Lastly, an accuracy assessment was conducted by comparing the results from the static and RTK observations using various statistical metrics. Figure 3 illustrates the methodological workflow, demonstrating the sequential steps undertaken in the study.

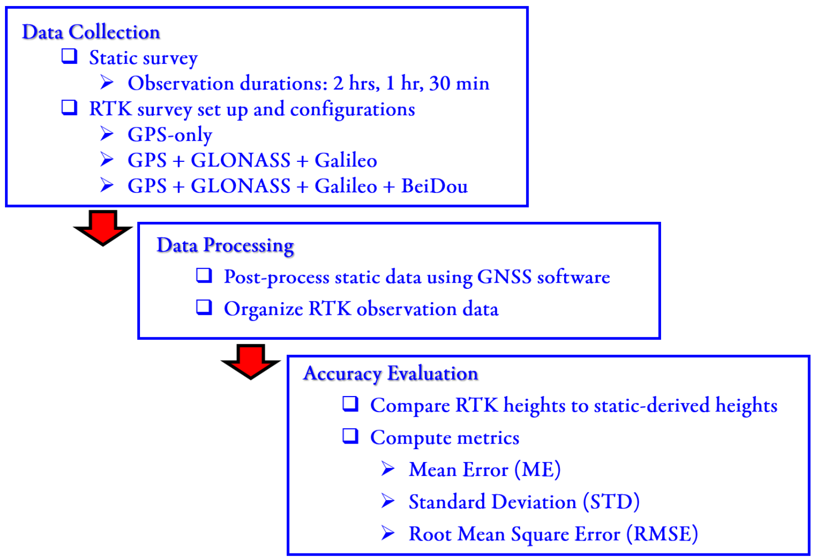

Figure 3. Methodology workflow

Static survey procedure

In this study, South Differential GNSS receivers were utilized to determine the horizontal and vertical positions of the twenty (20) selected unknown control stations. The GPS base receiver was set up at a reference station, with a temporary adjustment performed and all necessary precautions observed. The GPS rover receiver was mounted on a 2-meter pole supported by bipod legs and was systematically positioned over each control point. Observation sessions of 2 hours, 1 hour, and 30 minutes per point were conducted to ensure sufficient satellite tracking and enhance data quality for improved accuracy. The static data collection included observations from GPS, GLONASS, Galileo, and BeiDou constellations. The survey was conducted over a three-week period in October 2024.

The collected static GNSS data were post-processed using South GNSS Processor software (SW_GNSS_1.6.0.1) to compute the ellipsoidal heights, which served as the reference data for subsequent analysis.

RTK setup and configurations

The RTK surveys were conducted at different times from the static surveys in October 2024. All RTK measurements were referenced to a known control point, with the base station positioned approximately 2 kilometers from the study area. A custom rover setup was used, consisting of a GNSS receiver mounted on a 2-meter fixed-height pole stabilized by bipod legs. The receiver connected via Bluetooth to an Android device, with data logging managed through the GNSS data Logger application. Table 1 lists the instruments and software used during the GNSS surveys.

Table 1. Instruments and software used in the study

Item	Description
GNSS receiver model	South Differential GNSS receiver
GNSS antenna mount	2-meter fixed-height pole with bipod
RTK data Logging device	GNSS data Logger (Android)
Post-Processing software	South GNSS Processor (SW_GNSS_1.6.0.1)

The receiver was configured to evaluate three distinct satellite constellation scenarios: (1) GPS-only, (2) GPS + GLONASS + Galileo (GPS+GLO+GAL), and (3) GPS + GLONASS + Galileo + BeiDou (GPS+GLO+GAL+BDS). These configurations were selected based on commonly used GNSS survey setups in Africa. Configurations (1) and (2) were chosen because many previous studies assess the impact of adding GLONASS to GPS satellites, providing a benchmark for standard survey practices in the region. Configuration (3) incorporated all four available GNSS constellations to evaluate the maximum potential of using a multi-constellation approach.

A single RTK setup was used to collect data for all three configurations consecutively. Each configuration was tested under similar satellite conditions. Data collection at each control station lasted for 60 seconds if a "fixed" solution was obtained and 180 seconds (3 minutes) if the initial solution was "float." Extended observation times for float solutions aimed to give the receiver ample opportunity to achieve a fixed solution while maintaining consistency in the wait time for improved accuracy. This approach aligns with common surveying practices to enhance data reliability.

<u>Statistical accuracy assessment</u>

To assess the accuracy of the ellipsoidal heights obtained using multi-constellation RTK GNSS methods, three statistical metrics were employed: Mean Error (ME), Standard Deviation (STD), and Root Mean Square Error (RMSE), as defined in Equations (1)–(3).

$$\mathrm{ME} = \frac{\sum_{i=1}^{n} Y_i - X_i}{n} \tag{1}$$

$$\mathrm{STD} = \sqrt{\frac{\sum_{i=1}^{n}(X_i - \bar{X})^2}{n}} \tag{2}$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(Y_i - X_i)^2}{n}} \tag{3}$$

where:

y_i = ellipsoidal height value of each station from static GNSS survey, x_i = predicted ellipsoidal height values of each station from multi-constellation RTK survey, $\bar{x}$= average ellipsoidal height values of each station and n = number of points.

ME indicates the average error and helps identify systematic bias in the RTK measurements. STD describes the variability or spread of the errors, showing how consistent the results are. RMSE provides a comprehensive measure of overall accuracy by combining both the bias and variability in a single value. Lower values for ME, STD, and RMSE imply higher accuracy and consistency of the RTK results compared to the static survey reference.

Results and Discussion

To analyze the performance of different RTK configurations, we computed the absolute differences between the ellipsoidal heights obtained from each RTK setup and the corresponding ground truth static data for 2-hr, 1-hr, and 30-min observation sessions. Figure 4 provides a comparison of the ME and RMSE values across these configurations and durations, offering a clear visualization of their relative performance. Table 2 provides a concise summary of the results, offering a comparative overview of the minimum, maximum, ME, STD, and RMSE for each configuration and duration. To further illustrate the variations across different stations, Figures 5, 6, and 7 present detailed visualizations of the height discrepancies.

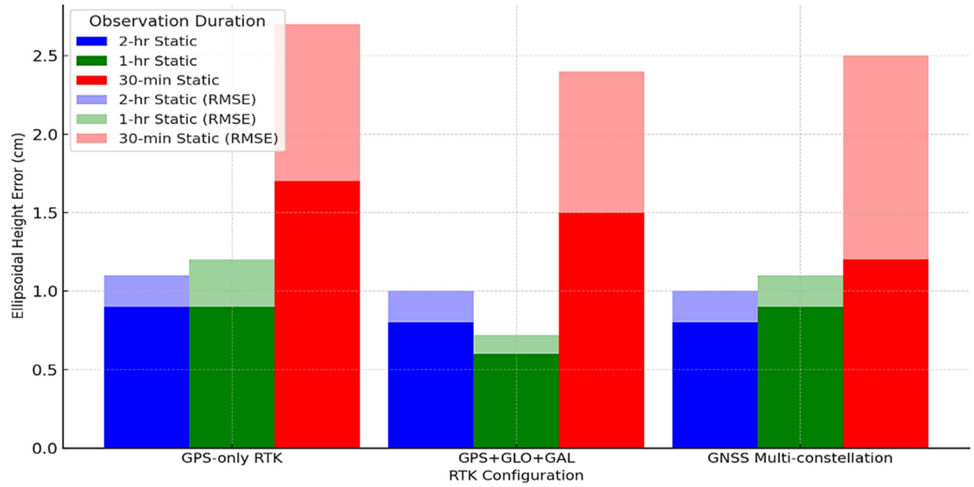

Figure 4. Comparison of RTK configuration performance for different observation durations

Figure 4 clearly illustrates that longer observation durations consistently result in lower measurement errors, with the 2-hour sessions yielding the most stable results across all configurations. The GPS+GLO+GAL configuration outperforms the GPS-only setup in terms of both ME and RMSE across all durations, demonstrating the benefits of multi-constellation integration. However, the 30-minute session results show that even multi-constellation setups struggle with height accuracy, as reflected by the increased RMSE values.

Table 2 summarizes the statistical performance of each RTK configuration across the three observation durations. For the 2-hour session, all setups achieved relatively low errors, with GPS-only RTK showing a maximum error of 2.60 cm and an RMSE of 1.10 cm. The GPS+GLO+GAL and GNSS multi-constellation configurations performed slightly better, each reducing the RMSE to 1.00 cm, reflecting improved stability with additional satellite signals. As the observation duration decreased to 1 hour, errors increased slightly. Notably, the GPS+GLO+GAL configuration maintained strong performance with an RMSE of 0.72 cm, while the GPS-only RTK rose to 1.20 cm. This highlights the benefit of multi-constellation integration for shorter sessions. In the 30-minute session, all configurations experienced a significant drop in accuracy. GPS-only RTK recorded an RMSE of 2.70 cm, while even the GNSS multi-constellation setup saw an increase to 2.50 cm, indicating that very short sessions lead to reduced measurement stability regardless of satellite configuration.

Table 2. Statistics of the differences between the ground truth static data of different sessions and multi-constellation RTK data

Ground truth	RTK configuration	Min (cm)	Max (cm)	ME (cm)	STD (cm)	RMSE (cm)
2-hr	GPS-only	0.00	2.60	0.90	0.70	1.10
	GPS+GLO+GAL	0.00	2.00	0.80	0.70	1.00
	GNSS	0.00	1.90	0.80	0.60	1.00
1-hr	GPS-only	0.01	3.10	0.90	0.80	1.20
	GPS+GLO+GAL	0.01	1.70	0.60	0.40	0.72
	GNSS	0.00	2.10	0.90	0.60	1.10
30-min	GPS-only	0.00	9.60	1.70	2.20	2.70
	GPS+GLO+GAL	0.00	9.20	1.50	2.00	2.40
	GNSS	0.00	10.30	1.20	2.20	2.50

Figure 5 shows the absolute height differences between the 2-hour static measurements and RTK-derived ellipsoidal heights across 20 stations. The GPS-only configuration exhibits the largest errors, particularly at stations 7 and 12, where deviations exceed 2 cm. The GNSS configuration generally performs better, with consistently smaller errors. The larger error spikes observed in the GPS-only configuration at stations 7 and 12 may be due to environmental factors like multipath effects, satellite geometry variations, or temporary atmospheric disturbances that impact RTK positioning accuracy.

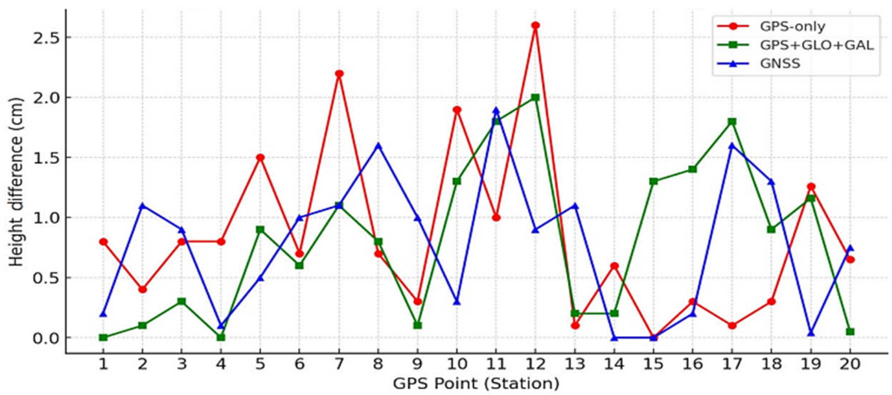

Figure 5. Absolute height differences between 2-hr static data and RTK GNSS observations

Figure 6 illustrates the discrepancies between the 1-hour static measurements and RTK-derived heights across the 20 stations. Compared to the 2-hour session, the height errors are generally larger, with noticeable fluctuations in the GPS-only configuration. The GPS+GLO+GAL and GNSS configurations show better consistency and reduced error magnitudes. However, stations 11 and 14 in the GPS-only setup exhibit error spikes above 2 cm, likely due to issues with satellite availability, cycle slips, or increased tropospheric effects.

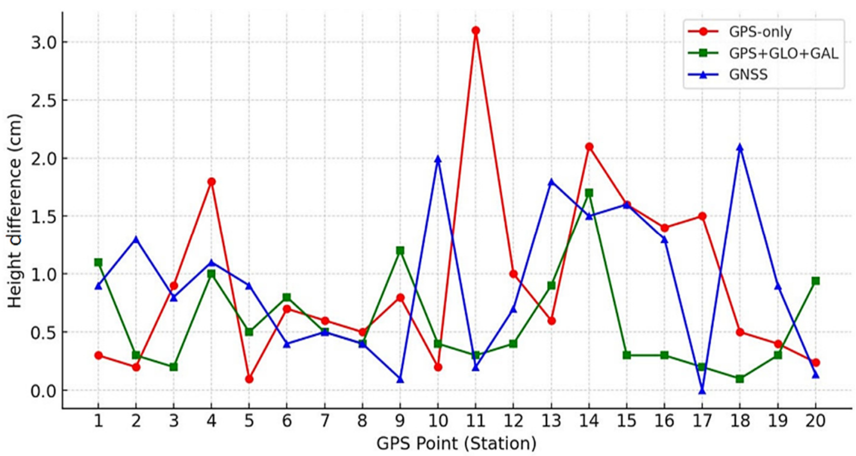

Figure 6. Absolute height differences between 1-hr static data and RTK GNSS observations

Figure 7 presents the height differences for the 30-minute static measurements compared to the RTK-derived heights. This session shows significantly larger errors compared to the 1-hour and 2-hour sessions. Notably, the GNSS configuration (GPS+GLO+GAL+BDS) shows the highest error, particularly at Station 9 (10.30 cm). This unexpected error spike may be linked to poor satellite geometry, potential multipath effects, or un-modelled atmospheric disturbances that impacted positioning accuracy during the short observation window.

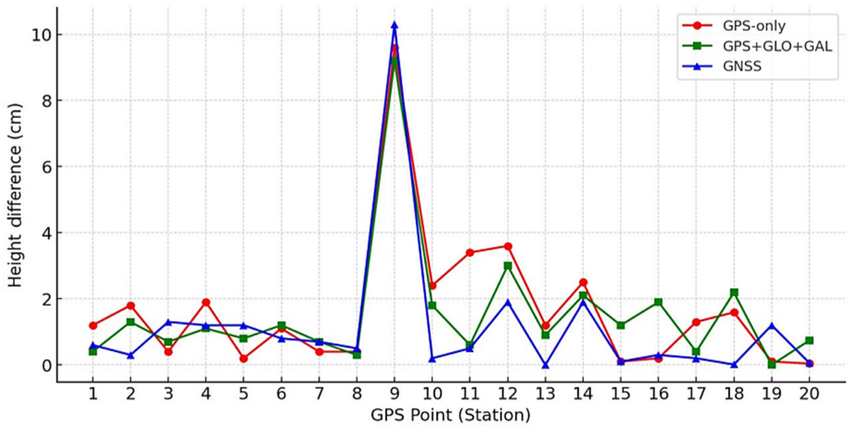

Figure 7. Absolute height differences between 30-min static data and RTK GNSS observations

Overall, the findings from this analysis demonstrate that longer observation durations result in significantly lower errors in height determination, regardless of the RTK GNSS configuration used. Multi-constellation RTK configurations (GPS+GLO+GAL and GNSS) consistently outperformed GPS-only solutions, particularly in reducing height measurement discrepancies during shorter observation periods. These results emphasize the importance of selecting appropriate observation durations based on the required level of positioning accuracy. Specifically, 2-hr sessions provided the most consistent and accurate results across all configurations, while 30-min sessions showed the largest deviations and least stability, strengthening the need for extended observation times in applications demanding high-precision height measurements.

Analysis of variance (ANOVA)

To assess and compare the different solutions, we applied the Analysis of Variance (ANOVA), a statistical method that examines whether the means of two or more groups originate from the same population (Jackson, 2023). ANOVA evaluates variability among groups using the F distribution and is based on the assumptions of equal variances, normal distribution of group means, and independence among observations (Rutherford, 2001). A one-way ANOVA was performed at a 95% confidence level ($\alpha = 0.05$) in Microsoft Excel, with the critical F-value determined to be 2.467. The formulated hypotheses were as follows:

Null hypothesis (H_0): $\mu_{GPS} = \mu_{GPS+GLO+GAL} = \mu_{GNSS}$

Alternative hypothesis (H_1): At least two or more means are significantly different from the others.

Following the ANOVA test conducted across the different observation sessions, the computed F-values for the 2-hr, 1-hr, and 30-min sessions were found to be 0.0617, 1.9103, and 0.3053, respectively, with corresponding p-values of 0.9403, 0.1574, and 0.7381. Given that in all cases, the computed F-values were significantly lower than the critical F-value (2.467) and the p-values exceeded the significance threshold of 0.05, we failed to reject the null hypothesis, indicating that no statistically significant difference exists between the height uncertainties obtained from the different RTK GNSS configurations.

This result means that the variations in ellipsoidal height measurements remain statistically comparable across the different GNSS configurations (GPS-only, GPS+GLONASS+Galileo, and GNSS multi-constellation). For practitioners, this suggests that users can expect comparable uncertainty regardless of the constellation configuration or observation duration. In practical terms, all configurations exhibit similar levels of uncertainty, and users can rely on them with equal confidence for accurate height measurements.

Conclusions

This study investigated the accuracy of height measurements obtained using multi-constellation RTK GNSS by comparing them against static ground truth data recorded over different observation periods (2-hr, 1-hr, and 30-min sessions). The results demonstrated that both the duration of static observations and the choice of satellite constellation configurations significantly impact the accuracy of RTK height measurements. Longer observation durations generally yielded lower errors, reinforcing the importance of extended observation times for precise positioning. Additionally, configurations incorporating multiple satellite constellations, particularly GPS+GLONASS+Galileo, provided more stable results with reduced variations compared to GPS-only solutions, particularly for shorter observation sessions. However, in the 30-min session, the GNSS configuration (GPS+GLONASS+Galileo+Beidou) exhibited the highest variations, with a maximum error of 10.30 cm observed at station 9, indicating potential issues with satellite geometry or signal disturbances at that location. The statistical analysis, including one-way ANOVA, revealed that the differences between the various RTK configurations were not statistically significant, suggesting that all configurations provide comparable levels of uncertainty in height determination. For high-accuracy applications under time constraints, using observation durations of at least 1 hour or 2 hours is recommended, as this will likely yield more stable results. Multi-constellation configurations, such as GPS+GLONASS+Galileo, are ideal for improving consistency, particularly in environments with variable satellite visibility. To achieve sub-decimeter vertical accuracy, longer observation durations (2 hours or more) should be prioritized. However, site-specific factors and satellite geometry should also be considered when selecting the RTK configuration and observation period. For users in resource-limited environments, especially where access to advanced GNSS equipment may be restricted, GPS-only setups may still provide acceptable accuracy when paired with longer observation times, although multi-constellation receivers are recommended for improved consistency and reliability under varied conditions. These findings highlight the potential benefits of multi-constellation RTK GNSS while also emphasizing the need for optimal observation periods and site-specific considerations when conducting precise height measurements.

Acknowledgements

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Conflict of Interests

The author declares that there are no conflicts of interest related to this article.

References

Abubakar T, Hermann NT (2021). Assessment of observations with GPS and GPS/GLONASS satellites in rapid static mode for precise point positioning. FUTY Journal of the Environment 15(1):93-103.

Allahyari M, Olsen MJ, Gillins DT, Dennis ML (2018). Tale of two RTNs: Rigorous evaluation of Real-Time Network GNSS observations. Journal of Surveying Engineering 144(2):05018001. *https://doi.org/10.1061/(ASCE)SU.1943-5428.0000249*

Castro-Arvizu JM, Medina D, Ziebold R (2020). Impact of Satellite Elevation Mask in GPS+ Galileo RTK Positioning. Institute of Navigation International Technical Meeting 2020, San Diego, California pp 487-498.

Dabove P (2019). The usability of GNSS mass-market receivers for cadastral surveys considering RTK and NRTK techniques. Geodesy and Geodynamics 10(4):282-289. *https://doi.org/10.1016/j.geog.2019.04.006*

El-Rabbany A (2006). Introduction to GPS: The Global Positioning System, Second Edition. Artech House pp 159-160.

Gillins D, Eddy M (2016). Comparison of GPS height modernization surveys using OPUS-Projects and following NGS-58 guidelines. Journal of Surveying Engineering 143(1):05016007. *https://doi.org/10.1061/(ASCE)SU.1943-5428.0000196*

He H (2010). Quality control of GPS RTK technology in road engineering. 2010 International Conference on Mechanic Automation and Control Engineering, Wuhan, China, 26-28 June 2010.

Hoffmann-Wellenhof B, Lichtenegger H, Wasle E (2008). GNSS-Global Navigation Satellite Systems: GPS, GLONASS, Galileo and More. Springer Science & Business Media.

Isioye OA, Moses M, Abdulmumin L (2018). Comparative Study of Some Online GNSS Post-Processing Services at Selected Permanent GNSS Sites in Nigeria. IntechOpen. *https://doi.org/10.5772/intechopen.79924*

Jackson SL (2013). Statistics: Plain and Simple. Boston, MA: Cengage Learning.

Janssen V (2009). A comparison of the VRS and MAC principles for network RTK. International Global Navigation Satellite Systems Society IGNSS Symposium, Qld, Australia pp 1-3.

Janssen V, Haasdyk J (2012). Assessment of Network RTK Performance using CORSnet NSW. International Global Navigation Satellite Systems Society IGNSS Symposium. University of New South Wales, Sydney, NSW, Australia pp 15-17.

Krzyzek R, Kudrys J (2022). Accuracy of GNSS RTK/NRTK height difference measurement. Applied Geomatics 14:491-499. *https://doi.org/10.1007/s12518-022-00450-2*

Langley RB, Teunissen PJ, Montenbruck O (2017). Introduction to GNSS. In: Teunissen P, Montenbruck O (Eds). Springer Handbook of Global Navigation Satellite Systems. Cham, Switzerland: Springer International Publishing.

Li X, Lv H, Ma F, Li X, Liu J, Jiang Z (2019). GNSS RTK positioning augmented with large LEO constellation. Remote Sensing 11(3):228. *https://doi.org/10.3390/rs11030228*

Luo X, Schaufler S, Branzanti M, Chen J (2020). Assessing the benefits of Galileo to high-precision GNSS positioning – RTK, PPP and post-processing. Advances in Space Research 68(12):4916-4931. *https://doi.org/10.1016/j.asr.2020.08.022*

Mi X, Zhang B, Yuan Y (2019). Multi-GNSS inter-system biases: Estimability analysis and impact on RTK positioning. GPS Solutions 23(3):81. *https://doi.org/10.1007/s10291-019-0873-8*

Msaewe HA, Hancock CM, Psimoulis P, Roberts GW, Bonenberg L, Ligt H de (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*

Odijk D (2017). GNSS algorithms and models. In: Teunissen P, Montenbruck O (Eds). Springer Handbook of Global Navigation Satellite Systems. Cham, Switzerland: Springer International Publishing.

Odolinski R, Denys P (2015). On the multi-GNSS RTK positioning performance in New Zealand. International Global Navigation Satellite Systems Society (IGNSS) Symposium, 2015 Jul 14, Gold Coast, Australia, pp 1-14.

Odolinski R, Teunissen PJG (2016). Single-frequency, dual-GNSS versus dual-frequency, single-GNSS: A low-cost and high-grade receivers GPS-BDS RTK analysis. Journal of Geodesy 90(11):1255–1278. *https://doi.org/10.1007/s00190-016-0921-x*

Odolinski R, Teunissen PJG (2019). An assessment of smartphone and low-cost multi-GNSS single-frequency RTK positioning for low, medium and high ionospheric disturbance periods. Journal of Geodesy 93(5):701-722. *https://doi.org/10.1007/s00190-018-1192-5*

Odolinski R, Teunissen PJG, Odijk D (2015). Combined BDS, Galileo, QZSS and GPS single-frequency RTK. GPS Solutions 19(1):151–163. *https://doi.org/10.1007/s10291-014-0376-6*

Ogutcu S (2019). Temporal correlation length of network-based RTK techniques. Measurement 134:539-547. *https://doi.org/10.1016/j.measurement.2018.10.099*

Omer FA, Ceren K, Sermet O, Salih A (2022). Comparative analysis of the performance of multi-GNSS RTK: A case study in Turkey. International Journal of Engineering and Geosciences 7(1):67-80.

Pirti A, Yucel M, Gumus K (2013). Testing real time kinematic GNSS (GPS and GPS/GLONASS) methods in obstructed and unobstructed sites. Geodetski Vestnik 57(3):498-512.

Raufu IO, Tata H (2022). Comparison of two corrector surface models of orthometric heights from GPS/levelling observations and global gravity model. Journal of Geospatial Information Science and Engineering 5(1):15-20. *https://doi.org/10.22146/jgise.72531*

Raufu IO, Tata H, Olaosegba S (2023). Modelling local geoid undulations using Unmanned Aerial Vehicles (UAVs): A case study of the Federal University of Technology, Akure, Nigeria. Geodesy, Cartography, and Aerial Photography 98(2):63-75. *https://doi.org/10.23939/istcgcap2023.98.063*

Rutherford A (2001). Introducing ANOVA and ANOVA: A GLM Approach. London: SAGE.

Tata H, Nzelibe IU, Raufu IO (2020). Assessing the accuracy of online GNSS processing services and commercial software on short baselines. South African Journal of Geomatics 9(2):321-332. *http://dx.doi.org/10.4314/sajg.v9i2.21*

Thom J, Odolinski R, McDonald L, Denys P (2019). On the use of between-baseline differenced and instantaneous RTK positioning while using simultaneous GNSS measurements. Survey Review 51(367):345-353. *https://doi.org/10.1080/00396265.2018.1460068*

Tian Y, Sui L, Xiao G, Zhao D, Tian Y (2019). Analysis of Galileo/BDS/GPS signals and RTK performance. GPS Solutions 23(2):37. *https://doi.org/10.1007/s10291-019-0831-5*

Tidey E, Odolinski R (2023). Low-cost multi-GNSS, single frequency RTK averaging for marine applications: accurate stationary positioning and vertical tide measurements. Marine Geodesy 46(4):333-358. *https://doi.org/10.1080/01490419.2023.2208289*

Tradacete M, Saez A, Arango JF, Huelamo CG, Revenga P, Barea R, Lopez Guillen E, Bergasa LM (2019). Positioning system for an electric autonomous vehicle based on the fusion of multi-GNSS RTK and odometry using an extended Kalman filter. Advances in Physical Agents. Advances in Intelligent Systems and Computing, Vol 855. Springer, Cham. *https://doi.org/10.1007/978-3-319-99885-5_2*

Weaver B, Gillins DT, Dennis M (2018). Hybrid survey networks: Combining Real-Time and Static GNSS observations for optimizing height modernization. Journal of Surveying Engineering 144(1):05017006. *https://doi.org/10.1061/(ASCE)SU.1943-5428.0000244*

Xi R, Chen H, Meng X, Jiang W, Chen Q (2018). Reliable dynamic monitoring of bridges with integrated GPS and BeiDou. Journal of Surveying Engineering 144(4):04018008. *https://doi.org/10.1061/(ASCE)SU.1943-5428.0000263*

Zhang K, Wu F, Wu S, Rizos C, Roberts C, Ge L, Yan T, Gordini C, Kealy A, Hale M, Ramm P, Asmussen H, Kinlyside D, Harcombe P (2006). Sparse or dense: Challenges of Australian Network RTK. Proceedings of International Global Navigation Satellite Systems Society Symposium (IGNSS2006), Surfers Paradise, Australia, 2006 Jul 17-21.