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# COMPARATIVE EVALUATION OF GNSS POSITIONING ACCURACY USING RTK TECHNIQUES AND CORS-BASED POST-PROCESSING SOLUTIONS

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## Abstract

Global Navigation Satellite System (GNSS) applications in Osun State, Nigeria, are limited by poor positional accuracy, particularly in vertical measurements. With the recent establishment of a Continuously Operating Reference Station (CORS) by private surveyors, it is important to assess the performance of real-time and post-processed GNSS solutions for local survey practice. This study compared two real-time kinematic (RTK) connection methods: radio frequency (RF) and network RTK via internet (NRTK) with static precise positioning using Canadian Spatial Reference System Precise Point Positioning (CSRS-PPP) and Osun CORS RINEX data processed in South Geomatics Office software. Field data were collected on three control stations with a Tersus Oscar GNSS receiver, and accuracy was evaluated using root mean square error (RMSE) against published control coordinates. Results show that CSRS-PPP (0.11 m easting, 0.17 m northing, 3.78 m height) and Osun CORS (0.09 m easting, 0.11 m northing, 3.76 m height) achieved horizontal accuracies within the allowable 0.05-0.50 m limit, but vertical errors exceeded the 0.10 m tolerance. NRTK (0.06 m easting, 0.03 m northing) performed better than RF-RTK (0.53 m easting, 1.29 m northing) for horizontal positioning, yet both produced unacceptable vertical errors of 24.14 m and 8.54 m, respectively. The findings confirm that online PPP and internet-based RTK provide reliable horizontal accuracy in Osun State, but vertical accuracy remains inadequate and requires further methodological improvement.

Keywords: CORS, GNSS, GNSS-PPP, RTK GNSS, Static Observation

## Introduction

The spatial foundation of any successful surveying activity lies in an accurate and reliable geodetic reference framework [1]. Traditionally, this framework has been established through networks of control points whose positions have been determined with high precision using mathematical models, least squares adjustments, and rigorous field measurements. These control networks provide the spatial referencing necessary to tie geospatial data to identifiable positions on Earth's surface. This ensures uniformity, interpretability, and interoperability across cadastral, engineering, and hydrographic applications [2][3].

Recent advancements in satellite-based positioning technologies, particularly the Global Navigation Satellite System (GNSS), have revolutionized geospatial data acquisition worldwide. Central to this evolution is the establishment of Continuously Operating Reference Stations (CORS), which are permanent GNSS reference stations providing real-time and post-processed correction services. CORS enable centimeter-level accuracy in positioning by broadcasting corrections via internet or radio frequency, thus replacing traditional reference stations and delivering consistent, high-precision data 24/7 [4][5]. Their widespread adoption has made them essential infrastructure for surveying, geodesy, navigation, and Earth observation [6][7][8].

In Nigeria, the Nigerian GNSS Reference Network (NIGNET) CORS form the backbone of the national spatial reference system and contribute to the continental African Geodetic Reference Frame (AFREF) [9][10]. However, the historical Nigerian triangulation system is not homogeneous, and suffers from inconsistent coordinate definitions due to varying degrees of observational precision and the use of different equipment over time [11][12]. This has prompted the establishment of additional CORS by both private firms and state governments.

The Osun CORS in Osogbo, Osun State, is one such initiative, offering GNSS users the ability to perform real-time kinematic (RTK) surveys via radio or internet, or to process static data using online services such as the Canadian Spatial Reference System-precise point positioning (CSRS-PPP) [13]. CSRS-PPP, developed by Natural Resources Canada, supports GPS and GLONASS data and has proven effective in processing static GNSS data to achieve centimeter-level positional accuracy [14][15]. Its accessibility and performance make it particularly suitable for users in developing regions.

Traditionally, the coordinates of control points are obtained using dual-receiver setups, with one unit acting as a reference station. However, this method is time-consuming and requires in-depth knowledge of GNSS processing software [15]. The availability of CORS now enables single-receiver operations, reducing field personnel and equipment costs while improving productivity. In this study, corrections were sourced from the Sacredion CORS in Osun State through its Networked Transport of RTCM via Internet Protocol (NTRIP) service. The CORS itself was treated as a trusted reference station; hence, no additional quality control was applied to its infrastructure. Instead, preliminary checks were carried out on the downloaded RINEX files to identify any signal interruptions before post-processing. Despite these advancements, empirical evaluations comparing the performance of RTK via radio and internet, and static observations corrected through post-processing, remain limited, particularly in the Nigerian context.

This study, therefore, aims to evaluate the practical utility of the Osun CORS for high-precision GNSS surveying in Osogbo, Nigeria, using: (i) RTK positioning via both radio frequency and internet connections, and (ii) single-receiver static observations processed through online platforms and the South Geomatics Office software, which applies least-squares adjustment and error modeling techniques. By examining these methods, the study contributes to a deeper understanding of GNSS implementation in Nigeria and provides insights for professionals seeking reliable and cost-effective surveying techniques.

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## Materials and Methods

### *Study Area*

The study was conducted in Osogbo, the capital city of Osun State, Nigeria. Osogbo is located at approximately latitudes 7° 40' N and 7° 59' N, and longitudes 4° 22' E and 4° 39' E, with an average elevation of about 336 meters above sea level. For the purpose of this research, three primary control points were strategically selected across the city to ensure even spatial distribution and to evaluate the performance of GNSS observations under diverse urban conditions, as illustrated in Figure 1. These points were chosen to provide representative coverage of different environments within Osogbo: an open park, a residential area with moderate vegetation and low-rise buildings, and a government administrative compound with open ground and occasional vehicle movement. Each control point was monumental with a permanent concrete pillar embedded with a brass survey mark, ensuring structural stability and long-term reliability for repeated GNSS observations. The points were located in areas with minimal environmental obstructions, reducing multipath and signal blockage while reflecting typical urban conditions. Additionally, all three points fall within the coverage area of the Sacredion Osun CORS network, enabling both real-time kinematic (RTK) and post-processed GNSS measurements. While the use of only three points limits broad statistical generalization, this selection allows a focused preliminary evaluation of GNSS positioning performance across varying urban scenarios.

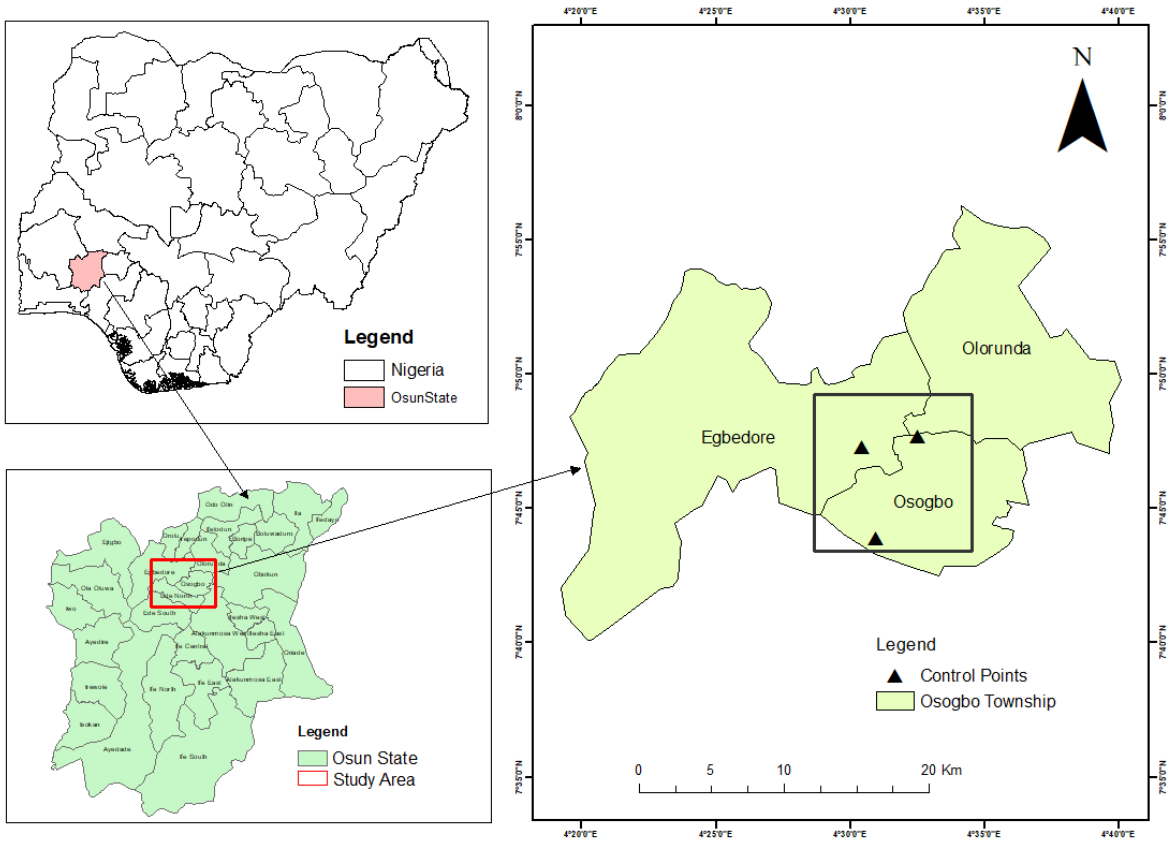



Figure 1. Map of the study area showing the spatial distribution of selected control points.

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***Method***

This study employed both primary and secondary geospatial data to evaluate the performance of different GNSS survey techniques using the Osun CORS station in Osogbo, Nigeria. The methodological framework involved the acquisition of field observations and subsequent processing through different platforms. Specifically, three GNSS survey methods were examined:

1. Real-Time Kinematic (RTK): rover observations corrected in real time using the Osun CORS reference station.

2. Static GNSS with Differential Post-Processing: static observations processed with commercial software (South Geomatics Office) using the Osun CORS reference data.

3. Static GNSS with Precise Point Positioning (PPP): static observations processed through an online service (CSRS-PPP).

***Data Sources and Quality Assurance***

Primary GNSS data were collected from three selected control points using a Tersus Oscar GNSS receiver. Each point was observed multiple times, and the average coordinates were computed to ensure positional accuracy. The official coordinates of the control points were obtained from the Office of the Surveyor General of Osun State (Table 1).

To validate the positional stability of the control points, the observed GNSS coordinates were compared with the official as-built coordinates. The results of this comparison (Table 2) indicate millimetre-level discrepancies in all components (E, N, and h), confirming that the points remain in situ and reliable for subsequent geodetic applications.

Table 1. Official Coordinates of Selected Control Points (Source: Office of the Surveyor General, Osun State)

| Station | Easting (m) | Northing (m) | Height (m) |
|---|---|---|---|
| FGP027 | 670027.499 | 861901.525 | 314.034 |
| OCSS113 | 666243.200 | 861170.655 | 336.131 |
| EDCS-1S | 667194.721 | 854944.182 | 339.884 |

Table 2. Differences between Observed GNSS and Official Coordinates

| Station | ΔE (m) | ΔY (m) | Δh (m) | Remark |
|---|---|---|---|---|
| FGP027 | < 0.005 | < 0.005 | < 0.010 | Stable |
| OCSS113 | < 0.005 | < 0.005 | < 0.010 | Stable |
| EDCS-1S | < 0.005 | < 0.005 | < 0.010 | Stable |

***GNSS Data Acquisition***

To assess the accuracy of GNSS positioning under varying configurations, three acquisition methods were implemented using the Tersus Oscar GNSS receiver. In the first setup, a pair of receivers was deployed, with one functioning as a reference station positioned over a known

control point and configured to transmit UHF-based differential corrections, while the second unit, mounted on a 2-meter survey pole stabilized by bipod legs, served as the rover and was centred over each control point to receive real-time corrections. Each point was observed for 60 seconds and repeated three times to determine average coordinates. The second method utilised the Osun State CORS station accessed via NTRIP over an internet connection, with the rover receiving real-time correction data directly from the virtual base, thereby eliminating the need for a local base station; this method also involved three 60-second observations per point. The third method involved a static observation mode, where a single receiver was precisely centred over each control point and operated for 60 minutes with observations recorded at 5-second intervals, logging high-quality RINEX data without real-time corrections.

***GNSS Data Processing***

The static-mode GNSS data collected (with observation sessions lasting approximately 1 hours per station) were processed using two approaches. First, the raw data, saved in Receiver Independent Exchange (RINEX**)** format to ensure interoperability, were post-processed using South Geomatics Office software. This processing was carried out in differential mode by integrating the corresponding RINEX data from the Osun CORS station, downloaded from the Sacredion website. The inclusion of local reference station data helped minimize atmospheric and orbital errors, thereby improving positional accuracy.

Second, the RINEX data were submitted to the Canadian Spatial Reference System–Precise Point Positioning (CSRS-PPP) online service, which utilises global GNSS reference networks and the latest International Terrestrial Reference Frame (ITRF2020) standards. Unlike differential processing, the CSRS-PPP approach does not depend on nearby base stations. Instead, it applies precise satellite orbit and clock products to achieve centimetre-level accuracy. Results were typically returned within five minutes via email.

For RTK positioning, the rover receivers logged observations in real time using RTCM (Radio Technical Commission for Maritime Services) corrections transmitted via a UHF radio link. Positional outputs were averaged across repeated occupation sessions to enhance reliability. All coordinates obtained from these methods were compared with the official control point coordinates provided by the Office of the Surveyor General of Osun State to assess accuracy and consistency.

***Accuracy Assessment***

To evaluate the positional accuracy of the GNSS observations, the coordinates (X, Y, and height) obtained from each acquisition method were compared against the official reference coordinates provided by the Office of the Surveyor General of Osun State. The differences between measured and reference coordinates were computed as coordinate residuals in the Easting (ΔX), Northing (ΔY), and Ellipsoidal height (Δh) components.

In addition to the root mean square error (RMSE), which was used as the primary indicator of overall positional accuracy for both horizontal (2D) and vertical components, mean error (ME) and standard deviation (SD) were also computed. The RMSE provides a measure of the overall magnitude of errors by combining both systematic and random components, thus reflecting the total positional accuracy. The mean error represents the average of the residuals and indicates

any systematic shift in the measured coordinates relative to the reference values. The standard deviation, on the other hand, measures the dispersion of the residuals around the mean, thereby reflecting the precision or repeatability of the measurements.

The statistical measures were calculated using the following formulas (Equations 1-3):

$$\text{ME} = \frac{\sum_{i=1}^{n} D_{Obs,i} - R_{Ref,i}}{n} \quad (1)$$

$$\text{SD} = \sqrt{\frac{\sum_{i=1}^{n}((D_{Obs,i} - R_{Ref,i}) - ME)^2}{n-1}} \quad (2)$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(D_{Obs,i} - R_{Ref,i})^2}{n}} \quad (3)$$

Where $D_{Obs,\,i}$ is the observed coordinate value for each control point, $R_{Ref,\,i}$ is the corresponding reference coordinate value, and n is the total number of control points. RMSE, mean error, and standard deviation were calculated separately for each coordinate component (Easting, Northing, and Height) to provide a comprehensive assessment of both accuracy and precision of the GNSS measurements.

**Results and Discussion**

The positional accuracy of GNSS observations obtained from four different acquisition and processing methods was evaluated against the official reference coordinates provided by the Office of the Surveyor General of Osun State. Table 2 presents the coordinate residuals (differences) for Easting, Northing, and Height components at each control point for the respective methods.

Table 2. Coordinate residuals between observed and reference coordinates.

| Station | Method | ΔX (m) | ΔY (m) | Δh (m) |
|---|---|---|---|---|
| FGP027 | **RTK-RF** | +0.440 | -1.586 | -7.667 |
| OCSS113 | | +0.300 | -1.445 | -5.232 |
| EDCS-1S | | +0.745 | -0.641 | -11.512 |
| FGP027 | **NRTK** | -0.039 | -0.035 | -24.771 |
| OCSS113 | | -0.035 | -0.017 | -22.959 |
| EDCS-1S | | +0.090 | +0.037 | -24.659 |
| FGP027 | **CSRS-PPP** | -0.158 | -0.068 | -3.871 |
| OCSS113 | | +0.079 | -0.251 | -3.604 |
| EDCS-1S | | +0.064 | +0.125 | -3.872 |
| FGP027 | **Osun CORS** | -0.090 | -0.171 | -3.632 |
| OCSS113 | | +0.014 | -0.067 | -4.054 |
| EDCS-1S | | +0.133 | -0.009 | -3.559 |

Table 3 presents the mean error (ME) and standard deviation (SD) values for each method. The ME indicates the average bias of the observations relative to the reference coordinates, while the SD reflects the consistency of the measurements. For the horizontal components, all methods show relatively small ME values (within ±0.5 m), with the NRTK, CSRS-PPP, and Osun CORS methods performing better than RTK-RF, which exhibited a higher bias particularly in the Northing direction (-1.224 m).

In terms of vertical positioning, the NRTK method showed the largest mean error (-24.130 m), suggesting a significant vertical bias, despite its relatively small SD (1.015 m). Conversely, CSRS-PPP and Osun CORS exhibited much smaller vertical biases (-3.782 m and -3.748 m, respectively) and low variability, making them more reliable for height determination. The RTK-RF method, although less biased than NRTK in height (-8.137 m), had higher variability (SD = 3.166 m), reflecting less stable vertical performance.

Table 3: Mean Error (ME) and Standard Deviation (SD) of positional accuracy for each GNSS acquisition and processing method.

| Method | ME X (m) | ME Y (m) | ME h (m) | SD X (m) | SD Y (m) | SD h (m) |
|---|---|---|---|---|---|---|
| RTK-RF | 0.495 | -1.224 | -8.137 | 0.228 | 0.510 | 3.166 |
| NRTK | 0.005 | -0.005 | -24.130 | 0.073 | 0.037 | 1.015 |
| CSRS-PPP | 0.005 | -0.065 | -3.782 | 0.133 | 0.188 | 0.154 |
| Osun CORS | 0.019 | -0.082 | -3.748 | 0.112 | 0.082 | 0.267 |

The RMSE values (Table 4) summarise the overall horizontal and vertical positional accuracy across the different GNSS acquisition and processing methods. To further illustrate the variation in positional accuracy, Figure 2 is presented, visually comparing the RMSE values for Easting, Northing, and Height components among the methods. The RTK method using a local base station with UHF radio frequency (RTK-RF) yielded moderate horizontal accuracy with RMSE values of 0.53 m (Easting) and 1.29 m (Northing), but exhibited relatively large vertical errors, with an RMSE of 8.54 m in height. The relatively large vertical discrepancy may be attributed to multipath effects, atmospheric conditions, and satellite geometry. However, dilution of precision (DOP) values, which would provide a quantitative measure of satellite geometry, were not logged during the field sessions. This limits our ability to directly assess the influence of geometry on the accuracy results. Nonetheless, previous studies have shown that elevated vertical dilution of precision (VDOP) values are common in real-time GNSS positioning and strongly amplify vertical errors [16,17]. This aligns with the pattern observed in this study, where real-time methods exhibited larger vertical RMSE compared to their horizontal counterparts. The RTK method utilising the Osun CORS via internet (NRTK) produced excellent horizontal accuracy (RMSE ≤ 0.06 m) but a significantly poorer vertical accuracy, with an RMSE height error of 24.14 m. This degradation in height accuracy could result from latency in correction data delivery, limited availability of vertically relevant satellites, or ionospheric delays affecting the correction stream [18]. However, these factors alone cannot fully explain such a systematic offset. A more probable explanation is a geoid–ellipsoid separation mismatch: the RTK solution likely reports ellipsoidal heights, whereas the

official reference coordinates are given in orthometric heights referenced to a local geoid model. This highlights the importance of clearly defining the vertical datum and applying appropriate geoid models when assessing GNSS-derived heights.

In contrast, the static PPP processing methods with both CSRS-PPP and Osun CORS differential post-processing demonstrated superior vertical accuracy, with height RMSEs below 4 m, alongside excellent horizontal precision (RMSE Easting and Northing < 0.2 m). These outcomes demonstrate the advantage of prolonged static observations coupled with high-precision post-processing algorithms that leverage global reference networks and updated terrestrial reference frames such as ITRF2020 [19][20].

The enhanced vertical accuracy observed in the static modes is consistent with existing literature emphasising that static GNSS surveys with post-processing corrections are more reliable for height determination than real-time methods [8]. The stable and longer observation sessions reduce random noise and multipath influences, while precise orbit and clock products used in CSRS-PPP and CORS processing further improve coordinate solutions.

Table 4: Summary of positional accuracy (RMSE) for each GNSS acquisition and processing method.

| Method | RMSE X (m) | RMSE Y (m) | RMSE h (m) |
|---|---|---|---|
| RTK-RF | 0.53 | 1.29 | 8.54 |
| NRTK | 0.06 | 0.03 | 24.14 |
| CSRS-PPP | 0.11 | 0.17 | 3.78 |
| Osun CORS | 0.09 | 0.11 | 3.76 |

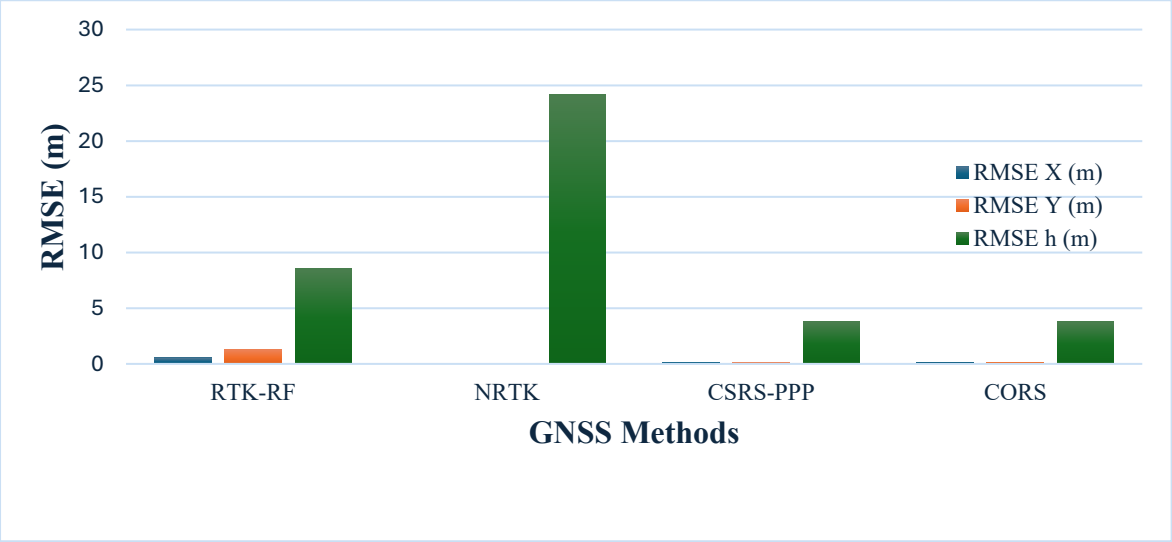



Figure 2. RMSE in (m) for different GNSS acquisition and processing methods

A comparative analysis of the four methods underscores the trade-offs between speed and accuracy in GNSS surveying. RTK methods provide rapid coordinate fixes suitable for real-time applications, although with compromised vertical precision, especially when using internet-based corrections. In contrast, static observation modes paired with post-processing significantly enhance accuracy but at the expense of longer survey durations and delayed data availability.

These findings reinforce the operational guidelines for GNSS use in Nigeria, as stipulated by the Office of the Surveyor General and the Nigerian Institution of Surveyors, which recommend static or hybrid GNSS processing for applications requiring strict vertical and geodetic control. Thus, for practitioners requiring sub-meter horizontal precision with moderate vertical tolerance, RTK via local base or NTRIP-based correction may be appropriate. However, for cadastral mapping, engineering design, and geodetic control frameworks, static data acquisition with CSRS-PPP or local CORS post-processing is recommended.

**Conclusion**

This study assessed the positional accuracy of various GNSS acquisition and processing methods using three known control stations in Osun State, Nigeria. Four different approaches were evaluated: RTK with UHF radio (RTK-RF), RTK via internet-based corrections (NRTK), static processing using the Canadian Spatial Reference System Precise Point Positioning service (CSRS-PPP), and static post-processing via Osun CORS. The results showed that while both RTK methods offered high horizontal precision suitable for general mapping and navigation purposes, their vertical accuracies were significantly lower, particularly for NRTK, with an RMSE height error exceeding 24 meters. Conversely, the static processing methods, especially those incorporating post-processing corrections, demonstrated superior accuracy in both horizontal and vertical components, with vertical RMSEs below 4 meters. These findings confirm that real-time GNSS techniques are practical for applications requiring rapid coordinate acquisition and sub-meter horizontal precision. However, for projects where vertical accuracy is critical, such as engineering surveying or topographic modelling, static data acquisition combined with post-processing is recommended. The study emphasises the importance of selecting appropriate GNSS strategies based on project requirements, terrain conditions, and accuracy demands. Based on the outcomes, the study recommends the adoption of the RTK via internet-based corrections method for horizontal point positioning due to its efficiency and accuracy. Additionally, it is advisable to utilise an online processing platform that is fast and aligns with the CORS for enhanced reliability. For detailing and survey activities with lower accuracy requirements, the RTK radio frequency method remains suitable, provided that careful observation procedures are followed. Moreover, the vertical height system in the study area requires further investigation to understand why none of the methods met the allowable vertical accuracy limits. Future work may focus on evaluating performance across a wider network of control points, over different time intervals, or during varying atmospheric conditions to further refine the understanding of GNSS method reliability in Nigeria and similar regions.

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