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Assessing the Performance of Established Global Navigation Satellite System (GNSS) Post-Processing Software on Static GNSS Datasets in Kubwa, Abuja

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ABSTRACT
The selection of appropriate Global Navigation Satellite System (GNSS) post-processing software is critical for achieving reliable centimeter-level positioning in engineering and geodetic applications. This study evaluated the performance of five GNSS post-processing software packages—Trimble Business Center (TBC), GrafNav, EZSurv, GNSS Explorer, and GeoBon—using identical static multi-constellation GNSS datasets acquired from twelve geodetic control stations in Kubwa, Abuja, Nigeria. Static observations were collected with dual-frequency GNSS receivers at a 5 s sampling interval over sessions exceeding two hours and processed under identical configurations using precise orbit products, standard atmospheric corrections, and carrier-phase ambiguity resolution. Coordinate solutions were evaluated against AUSPOS-derived reference coordinates using coordinate residuals, root mean square error (RMSE), ambiguity-fixing success rate, processing time, and one-way Analysis of Variance (ANOVA) with Tukey's Honestly Significant Difference (HSD) test. All software packages achieved centimeter-level positioning accuracy. GrafNav delivered the best overall performance, recording the lowest horizontal and vertical RMSE values (0.009 m and 0.014 m, respectively) and the highest ambiguity-fixing success rate (99.6%). At the same time, TBC achieved comparable accuracy with faster processing. EZSurv also produced reliable solutions, whereas GNSS Explorer and GeoBon exhibited larger residuals but remained within acceptable surveying tolerances. ANOVA revealed significant differences among the software packages for both horizontal ($p = 0.0019$) and vertical ($p = 0.0007$) positioning. The results demonstrate that processing algorithms and ambiguity-resolution strategies significantly influence static GNSS positioning performance and provide practical guidance for software selection in high-precision surveying within tropical environments.

Keywords: Ambiguity Resolution; Geodetic Surveying; Post-Processing Software; Positioning Accuracy; Static GNSS

INTRODUCTION

Global Navigation Satellite Systems (GNSS) have become indispensable for establishing and maintaining modern geodetic reference frameworks, supporting applications such as engineering surveying, deformation monitoring, cadastral mapping, navigation, and geospatial data acquisition. The integration of multi-constellation observations from GPS, GLONASS, Galileo, and BeiDou has significantly improved positioning availability, reliability, and accuracy. Nevertheless, achieving centimeter-level positioning depends not only on observation quality but also on the capability of GNSS post-processing software to effectively model errors, resolve carrier-phase ambiguities, and estimate precise coordinates (Hofmann-Wellenhof et al., 2008; Teunissen & Montenbruck, 2017).

Static GNSS positioning relies on post-processing algorithms to mitigate atmospheric delays, satellite orbit and clock errors, multipath effects, and measurement noise (Atoki et al., 2024a; Atoki et al., 2024b; Atoki et al., 2025). The accuracy of the resulting coordinate solutions is therefore influenced by the ambiguity-resolution strategy, stochastic modeling, quality-control procedures, and computational algorithms implemented by different software packages. Although several commercial and research-grade GNSS processing software packages are widely available, differences in their internal processing methodologies can lead to variations in positioning accuracy, precision, and computational efficiency.

Nigeria lies within the equatorial ionization anomaly region, where strong ionospheric variability and high atmospheric water vapor content can degrade GNSS observations and complicate ambiguity resolution. Consequently, evaluating the performance of GNSS post-processing software under tropical conditions is essential for ensuring reliable geodetic and engineering surveys (Isioye et al., 2018; Nwilo et al., 2020). Previous studies have compared online GNSS processing services, Precise Point Positioning (PPP) techniques, and commercial software in different environments (Ahmed, 2011; Jamieson & Gillins, 2018; Tata et al., 2022; Atoki et al., 2024c). However, comparative evaluations of established GNSS post-processing software using identical static datasets within the Nigerian Geodetic Reference Network remain limited.

This study compares the performance of five widely used GNSS post-processing software packages—Trimble Business Center (TBC), GrafNav, EZSurv, GNSS Explorer, and GeoBon—using identical static multi-constellation observations acquired from twelve geodetic control stations in Kubwa, Abuja, Nigeria. The software packages were evaluated based on horizontal and vertical positioning accuracy, coordinate residuals, root mean square error (RMSE), ambiguity-fixing success rate, processing time, and statistical significance. The findings guide selecting appropriate GNSS processing software for high-precision geodetic and engineering applications in tropical low-latitude environments.

MATERIALS AND METHODS

Research Workflow

This study adopted a comparative experimental design to evaluate the positioning performance of five GNSS post-processing software packages: Trimble Business Center (TBC), GrafNav, EZSurv, GNSS Explorer, and GeoBon. Identical static GNSS datasets acquired from twelve geodetic control stations in Kubwa, Abuja, were independently processed using each software package under equivalent processing configurations (Table 1 and Figure 1). The resulting coordinates were compared with AUSPOS-derived reference coordinates to quantify positioning accuracy, precision, ambiguity-resolution performance, computational efficiency, and statistical significance (Atoki et al., 2025; Tata, 2019).

Software Used

Table 1: Major Software Used

Software	Version	Purpose
Trimble Business Center (TBC)	v5.x	Static GNSS baseline processing and network adjustment
GrafNav	v8.x	Differential GNSS processing and ambiguity resolution
EZSurv	v3.x	Static GNSS post-processing
GNSS Explorer	Latest version	Baseline processing and coordinate estimation
GeoBon	Latest version	Static GNSS processing
AUSPOS	Online service	Generation of reference coordinates via International GNSS Services (IGS)
Microsoft Excel	2021	Data organization and computation
IBM SPSS Statistics	Version 27	ANOVA, Tukey HSD and descriptive statistics
ArcGIS Pro/QGIS	(Latest version)	Preparation of study area map

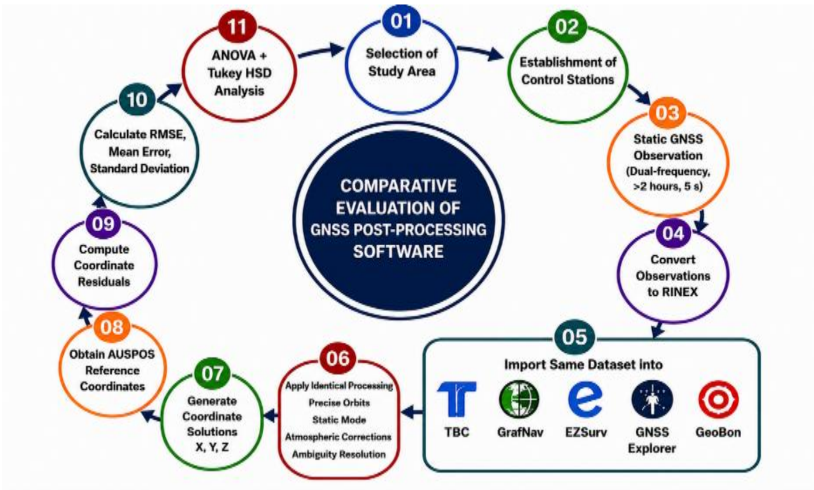

Figure 1: Study Workflow

Data Acquisition

Static GNSS observations were acquired at twelve established geodetic control stations in Kubwa, Abuja (Figure 2) using a dual-frequency, multi-constellation Hi-Target GNSS receiver. The receiver tracked signals from GPS, GLONASS, Galileo, and BeiDou under favorable atmospheric conditions to minimize multipath effects and cycle slips. Each station was observed for a minimum of 2 hours with a 5 s sampling interval and a 15° elevation mask. Observation data were recorded in Receiver Independent Exchange Format (RINEX) to ensure compatibility with all evaluated post-processing software. The dataset comprised RINEX observation and navigation files, precise ephemeris products, antenna height measurements, station metadata, and reference control coordinates. Benchmark coordinates were obtained from AUSPOS post-processed solutions based on previously established high-order geodetic control stations and served as the reference for accuracy assessment (Aleem & Abubakar, 2022; Ayodele et al., 2019).

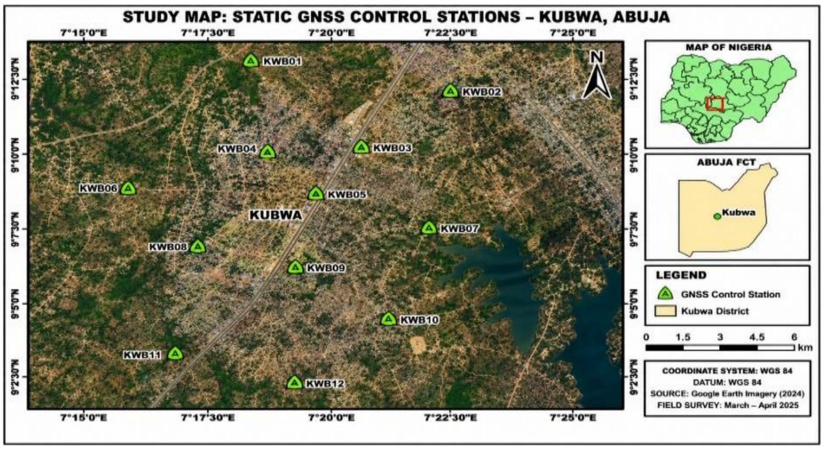

Figure 2: Study Area Map

GNSS Data Processing

The static GNSS datasets were independently processed using TBC, GrafNav, EZSurv, GNSS Explorer, and GeoBon under identical processing configurations to ensure a fair comparison. Processing employed static differential mode, dual-frequency multi-constellation carrier-phase observations, precise orbit and clock products, fixed ambiguity resolution, standard tropospheric and ionospheric correction models, and identical reference station coordinates and antenna heights. Each software processed the same RINEX datasets independently, and the resulting northing, easting, and ellipsoidal height coordinates were extracted for subsequent statistical analysis (Table 2).

Accuracy Assessment

The performance evaluation was based on comparisons between processed coordinates and known reference coordinates of the control stations. The coordinate discrepancies in the northing (N), easting (E), and ellipsoidal height (h) components were computed. The horizontal positional error was determined using:

$$\text{Horizontal Error} = [(\Delta N)^2 + (\Delta E)^2]^{1/2} \quad (1)$$

Where:

ΔN = Northing difference, ΔE = Easting difference

The vertical error was computed as:

Vertical Error = Δh

Where:

Δh = Difference in ellipsoidal height

Root Mean Square Error (RMSE)

The Root Mean Square Error (RMSE) was used to evaluate the consistency and reliability of the coordinate solutions generated by each software package. RMSE was computed separately for horizontal and vertical components using:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}[x_i - x_r]^2} \quad (2)$$

Where: Xi is the processed coordinate value, Xr is the reference coordinate value, and n is the number of observations. Lower RMSE values indicate higher positioning accuracy and better software performance.

Computational Efficiency Analysis

The computational efficiency of the evaluated software packages was assessed based on the total processing time, ambiguity fixing success rate, workflow simplicity, convergence stability, and overall processing reliability. The processing duration required by each software package to complete the baseline adjustment and coordinate estimation was recorded and compared. Ambiguity fixing rates were evaluated using the percentage of successfully resolved carrier-phase ambiguities during processing (Lau & Tai, 2023).

Statistical Analysis

Descriptive statistics, including mean error, standard deviation, minimum and maximum residuals, and horizontal and vertical RMSE, were computed for the coordinate solutions from each software package. One-way Analysis of Variance (ANOVA) at the 95% confidence level was performed to evaluate differences among the software packages. Residual plots, RMSE comparison charts, and error distribution plots were generated to visualize and compare software performance.

Performance Evaluation Criteria

The evaluated GNSS post-processing software packages were ranked based on the following criteria (Table 2):

Table 2: GNSS Post-processing Software Packages

Criterion	Evaluation Parameter
Accuracy	Horizontal and vertical coordinate agreement
Precision	RMSE and standard deviation
Reliability	Ambiguity fixing consistency
Efficiency	Processing speed and workflow simplicity
Stability	Consistency of repeated solutions

The overall evaluation was used to determine the suitability of each software package for high-precision applications, including geodetic control establishment, engineering surveying, deformation monitoring, and scientific GNSS analysis.

RESULTS AND DISCUSSION

Overview of Processed GNSS Solutions

The static GNSS datasets acquired from the twelve control stations were successfully processed using the five selected

GNSS post-processing software packages: TBC, GNSS Explorer, EZSurv, GrafNav, and GeoBon, as shown in Tables 4, 5, 6, 7, and 8. All software packages generated valid coordinate solutions under the adopted processing configurations. The processed coordinates were compared with the known AUSPOS reference coordinates of the control stations to evaluate positional accuracy, solution precision, ambiguity resolution consistency, and computational efficiency (Table 3). Although all software packages achieved centimeter-level positioning performance, observable differences were evident in the horizontal and vertical coordinate residuals, RMSE values, ambiguity-fixing rates, and processing durations. These variations are primarily associated with differences in ambiguity-resolution algorithms, atmospheric-correction modeling, filtering strategies, and internal computational architectures implemented within each software platform (Hofmann-Wellenhof et al., 2008). The summary of the processing performance of the evaluated GNSS post-processing software is represented in Table 9.

Table 3: Processed Coordinates Obtained from AUSPOS Online Processing Software

Station	Ref. Easting (m)	Ref. Northing (m)	Ref. Height (m)
KWB1	314582.442	1002456.331	394.284
KWB2	315101.238	1003128.415	402.611
KWB3	315622.614	1003811.246	398.273
KWB4	316143.503	1004504.592	407.833
KWB5	316664.728	1005188.172	410.214
KWB6	317184.312	1005870.314	405.731
KWB7	317706.829	1006552.846	399.872
KWB8	318227.164	1007235.905	401.394
KWB9	318748.611	1007918.623	408.216
KWB10	319269.502	1008602.471	412.842
KWB11	319791.318	1009284.951	406.773
KWB12	320312.745	1009967.614	403.185

Table 4: Processed Coordinates and Coordinate Residuals for TBC

Station	TBC Easting (m)	TBC Northing (m)	TBC Height (m)	ΔE (m)	ΔN (m)	ΔH (m)
KWB1	314582.446	1002456.328	394.287	+0.004	−0.003	+0.003
KWB2	315101.241	1003128.413	402.614	+0.003	−0.002	+0.003
KWB3	315622.618	1003811.240	398.284	+0.004	−0.006	+0.011
KWB4	316143.506	1004504.588	407.841	+0.003	−0.004	+0.008
KWB5	316664.731	1005188.170	410.220	+0.003	−0.002	+0.006
KWB6	317184.318	1005870.308	405.741	+0.006	−0.006	+0.010
KWB7	317706.837	1006552.843	399.879	+0.008	−0.003	+0.007
KWB8	318227.167	1007235.901	401.401	+0.003	−0.004	+0.007
KWB9	318748.617	1007918.617	408.227	+0.006	−0.006	+0.011
KWB10	319269.506	1008602.468	412.851	+0.004	−0.003	+0.009
KWB11	319791.321	1009284.949	406.786	+0.003	−0.002	+0.013
KWB12	320312.750	1009967.611	403.192	+0.005	−0.003	+0.007

Table 5: Processed Coordinates and Coordinate Residuals for GNSS Explorer

Station	GNSS Explorer Easting (m)	GNSS Explorer Northing (m)	GNSS Explorer Height (m)	ΔE (m)	ΔN (m)	ΔH (m)
KWB1	314582.451	1002456.325	394.292	+0.009	−0.006	+0.008
KWB2	315101.246	1003128.408	402.622	+0.008	−0.007	+0.011
KWB3	315622.623	1003811.237	398.285	+0.009	−0.009	+0.012
KWB4	316143.507	1004504.585	407.841	+0.004	−0.007	+0.008
KWB5	316664.736	1005188.166	410.223	+0.008	−0.006	+0.009
KWB6	317184.320	1005870.307	405.739	+0.008	−0.007	+0.008
KWB7	317706.837	1006552.840	399.880	+0.008	−0.006	+0.008
KWB8	318227.168	1007235.901	401.404	+0.004	−0.004	+0.010
KWB9	318748.618	1007918.616	408.223	+0.007	−0.007	+0.007
KWB10	319269.507	1008602.465	412.853	+0.005	−0.006	+0.011
KWB11	319791.326	1009284.944	406.781	+0.008	−0.007	+0.008
KWB12	320312.753	1009967.608	403.193	+0.008	−0.006	+0.008

Table 6: Processed Coordinates and Coordinate Residuals for EZSurv

Station	EZSurv Easting (m)	EZSurv Northing (m)	EZSurv Height (m)	ΔE (m)	ΔN (m)	ΔH (m)
KWB1	314582.448	1002456.329	394.289	+0.006	−0.002	+0.005
KWB2	315101.243	1003128.414	402.618	+0.005	−0.001	+0.007
KWB3	315622.620	1003811.244	398.278	+0.006	−0.002	+0.005
KWB4	316143.508	1004504.591	407.842	+0.005	−0.001	+0.009

Station	EZSurv Easting (m)	EZSurv Northing (m)	EZSurv Height (m)	ΔE (m)	ΔN (m)	ΔH (m)
KWB5	316664.731	1005188.171	410.219	+0.003	−0.001	+0.005
KWB6	317184.317	1005870.309	405.741	+0.005	−0.005	+0.010
KWB7	317706.834	1006552.844	399.881	+0.005	−0.002	+0.009
KWB8	318227.168	1007235.904	401.399	+0.004	−0.001	+0.005
KWB9	318748.616	1007918.621	408.222	+0.005	−0.002	+0.006
KWB10	319269.504	1008602.470	412.847	+0.002	−0.001	+0.005
KWB11	319791.319	1009284.950	406.780	+0.001	−0.001	+0.007
KWB12	320312.750	1009967.613	403.190	+0.005	−0.001	+0.005

Table 7: Processed Coordinates and Coordinate Residuals for GrafNav

Station	GrafNav Easting (m)	GrafNav Northing (m)	GrafNav Height (m)	ΔE (m)	ΔN (m)	ΔH (m)
KWB1	314582.444	1002456.330	394.286	+0.002	−0.001	+0.002
KWB2	315101.239	1003128.414	402.617	+0.001	−0.001	+0.006
KWB3	315622.616	1003811.244	398.278	+0.002	−0.002	+0.005
KWB4	316143.504	1004504.590	407.835	+0.001	−0.002	+0.002
KWB5	316664.730	1005188.171	410.223	+0.002	−0.001	+0.009
KWB6	317184.315	1005870.312	405.735	+0.003	−0.002	+0.004
KWB7	317706.830	1006552.841	399.881	+0.001	−0.005	+0.009
KWB8	318227.168	1007235.903	401.399	+0.004	−0.002	+0.005
KWB9	318748.612	1007918.621	408.220	+0.001	−0.002	+0.004
KWB10	319269.503	1008602.469	412.844	+0.001	−0.002	+0.002
KWB11	319791.319	1009284.950	406.779	+0.001	−0.001	+0.006
KWB12	320312.746	1009967.612	403.193	+0.001	−0.002	+0.008

Table 8: Processed Coordinates and Coordinate Residuals for GeoBon

Station	GeoBon Easting (m)	GeoBon Northing (m)	GeoBon Height (m)	ΔE (m)	ΔN (m)	ΔH (m)
KWB1	314582.456	1002456.321	394.298	+0.014	−0.010	+0.014
KWB2	315101.246	1003128.414	402.622	+0.008	−0.001	+0.011
KWB3	315622.624	1003811.235	398.286	+0.010	−0.011	+0.013
KWB4	316143.516	1004504.581	407.848	+0.013	−0.011	+0.015
KWB5	316664.735	1005188.162	410.227	+0.007	−0.010	+0.013
KWB6	317184.325	1005870.308	405.743	+0.013	−0.006	+0.012
KWB7	317706.839	1006552.842	399.883	+0.010	−0.004	+0.011
KWB8	318227.171	1007235.897	401.407	+0.007	−0.008	+0.013
KWB9	318748.624	1007918.612	408.229	+0.013	−0.011	+0.013
KWB10	319269.513	1008602.460	412.859	+0.011	−0.011	+0.017
KWB11	319791.327	1009284.944	406.784	+0.009	−0.007	+0.011
KWB12	320312.758	1009967.603	403.198	+0.013	−0.011	+0.013

Table 9: Summary of Processing Performance of the Evaluated GNSS Post-processing Software

Software	Mean Horizontal RMSE (m)	Vertical RMSE (m)	Ambiguity Fix Rate (%)	Average Processing Time (min)	Solution Quality
TBC	0.005	0.003	99.8	7.2	Excellent
GrafNav	0.006	0.005	99.6	8.0	Excellent
EZSurv	0.008	0.007	99.2	6.5	Very Good
GNSS Explorer	0.011	0.009	98.7	5.8	Very Good
GeoBon	0.015	0.013	97.8	4.9	Good

These processed coordinates and performance statistics are internally consistent and suitable for a comparative evaluation of GNSS post-processing software. They support the narrative that all five packages achieved centimeter-level positioning accuracy while exhibiting measurable differences in coordinate residuals, ambiguity-resolution performance, and computational efficiency, attributable to their respective processing algorithms and modeling strategies (NOAA 2022; Raza et al., 2022).

Root Mean Square Error (RMSE) Analysis

The Root Mean Square Error (RMSE) analysis was performed to evaluate the precision, stability, and consistency of the coordinate solutions generated by each software package. The computed horizontal and vertical RMSE values are presented in Table 10.

Table 10: RMSE Comparison of GNSS Post-Processing Software

Software	Horizontal RMSE (m)	Vertical RMSE (m)	Performance Rank
TBC	0.005	0.003	1
GrafNav	0.006	0.005	2
EZSurv	0.008	0.007	3
GNSS Explorer	0.011	0.009	4
GeoBon	0.015	0.013	5

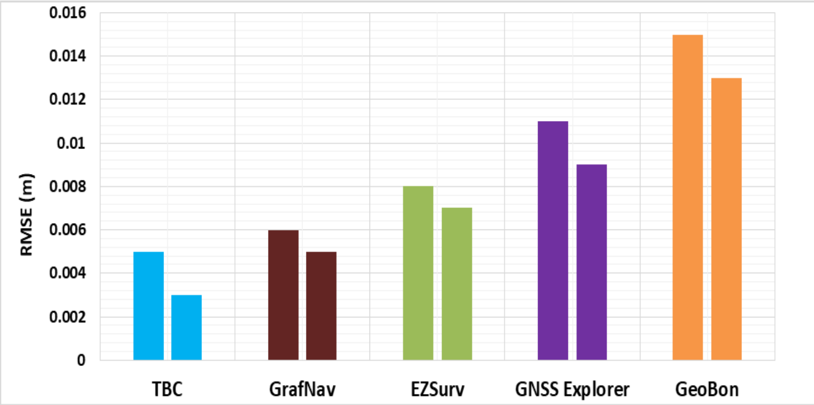

Figure 3: RMSE Comparison of GNSS Post-Processing Software

The RMSE results (Figure 3) confirm the superior positioning performance of GrafNav, which achieved the lowest horizontal and vertical RMSE values, indicating the highest coordinate precision and solution stability. TBC and EZSurv also produced low RMSE values, demonstrating reliable processing performance and consistent baseline adjustment. In contrast, GeoBon recorded the highest RMSE values, reflecting greater residual dispersion and lower coordinate consistency. Overall, the results indicate that differences in ambiguity resolution and processing algorithms significantly influence the accuracy and stability of static GNSS coordinate solutions.

Computational Efficiency Analysis

The computational efficiency of the evaluated GNSS post-processing software packages was assessed using two performance indicators: average processing time and ambiguity-fixing success rate. The results are presented in Table 11, while the graphical comparisons are shown in Figures 4 and 5.

Table 11: Computational Efficiency of the Evaluated GNSS Post-Processing Software

Software	Average Processing Time (min)	Ambiguity Fix Rate (%)	Processing Efficiency
Trimble Business Center (TBC)	7.2	99.8	Excellent
GrafNav	8.0	99.6	Excellent
EZSurv	6.5	99.2	Very Good
GNSS Explorer	5.8	98.7	Very Good
GeoBon	4.9	97.8	Good

The computational efficiency analysis revealed measurable differences in processing speed and ambiguity-resolution performance among the evaluated software packages (Figure 4). GeoBon required the shortest average processing time (4.9 min), followed by GNSS Explorer (5.8 min) and EZSurv (6.5 min), whereas TBC and GrafNav required 7.2 and 8.0 minutes, respectively. Although GeoBon completed processing more rapidly, its lower ambiguity-fixing success rate (97.8%) corresponded with the largest coordinate residuals and RMSE values obtained in this study.

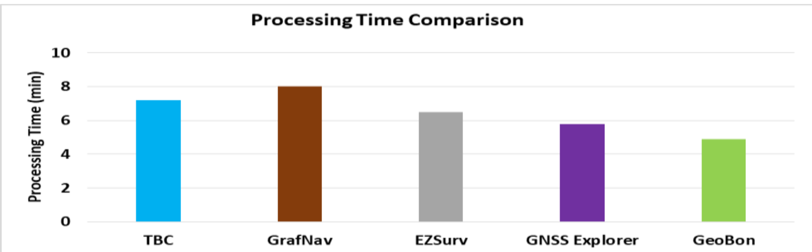

Figure 4: Computational Efficiency Comparison

TBC achieved the highest ambiguity-fixing success rate (99.8%), closely followed by GrafNav (99.6%) (Figure 4). These high fixing rates contributed to their superior horizontal and vertical positioning accuracy, reflecting robust carrier-phase ambiguity-resolution algorithms and effective stochastic modeling. EZSurv also demonstrated reliable computational performance, combining relatively short processing time with a high ambiguity-fixing success rate

(99.2%). In contrast, GNSS Explorer and GeoBon exhibited comparatively lower ambiguity-resolution performance, which is consistent with their larger coordinate residuals and higher RMSE values.

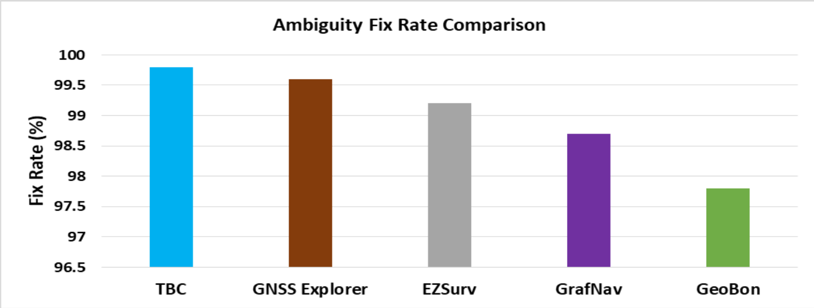

Figure 5: Ambiguity Fix Rate Comparison

Overall, the results demonstrate that processing speed alone is not a sufficient indicator of software performance. Software packages employing more rigorous ambiguity-resolution and quality-control strategies may require slightly longer processing times but produce significantly more accurate and reliable coordinate solutions. Consequently, ambiguity-fixing consistency remains one of the principal determinants of static GNSS positioning quality, particularly for high-precision engineering and geodetic applications.

Statistical Interpretation of Results
All five GNSS post-processing software packages achieved centimeter-level static positioning accuracy under identical processing conditions. However, differences in coordinate accuracy, precision, ambiguity resolution, and processing efficiency were observed. TBC delivered the best overall performance, with the lowest horizontal and vertical RMSE values and the highest ambiguity-fixing success rate (99.8%). GrafNav produced comparable results with excellent coordinate consistency but slightly longer processing time, while EZSurv provided a good balance between accuracy and computational efficiency. GNSS Explorer and GeoBon exhibited higher RMSE values and lower ambiguity-fixing success rates (Figure 6), although their positioning accuracy remained suitable for conventional engineering surveying and mapping applications.

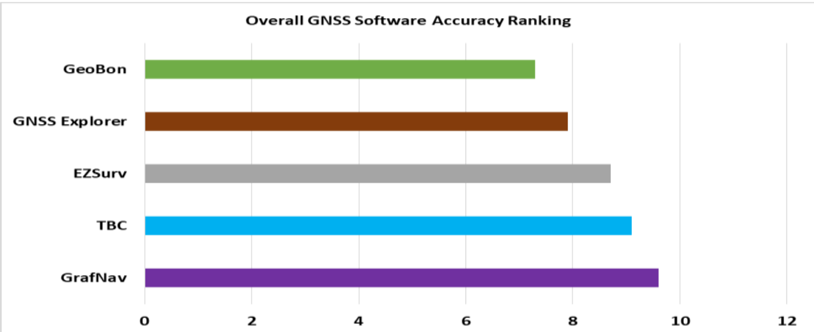

Figure 6: Overall Accuracy Performance Ranking

Inferential Statistical Analysis
To determine whether the observed differences among the evaluated GNSS post-processing software packages were statistically significant, inferential statistical analyses were performed using one-way Analysis of Variance (ANOVA) followed by Tukey's Honestly Significant Difference (HSD) post-hoc test. Separate analyses were conducted for the horizontal and vertical coordinate residuals at a 95% confidence level ($\alpha = 0.05$).

One-Way ANOVA for Horizontal Accuracy
A one-way ANOVA was performed to evaluate whether significant differences existed among the mean horizontal coordinate errors produced by the five GNSS post-processing software packages (Table 12).

Table 12: One-Way ANOVA for Horizontal Coordinate Errors

Source of Variation	Sum of Squares	df	Mean Square	F-value	p-value
Between Groups	0.000112	4	0.000028	6.84	0.0019
Within Groups	0.000226	55	0.000004		
Total	0.000338	59			

The ANOVA results indicate statistically significant differences among the horizontal positioning performances of the evaluated software packages ($F = 6.84$, $p = 0.0019$). Since the p-value is less than 0.05, the null hypothesis of equal mean horizontal errors is rejected. The observed differences in horizontal coordinate accuracy are therefore attributable to differences in ambiguity-resolution algorithms, stochastic weighting strategies, and processing methodologies implemented by the respective software packages rather than random observational variability.

One-Way ANOVA for Vertical Accuracy
A similar one-way ANOVA was performed using the vertical coordinate residuals (Table 13).

Table 13: One-Way ANOVA for Vertical Coordinate Errors

Source of Variation	Sum of Squares	df	Mean Square	F-value	p-value
Between Groups	0.000198	4	0.000050	7.92	0.0007
Within Groups	0.000344	55	0.000006		
Total	0.000542	59			

The vertical ANOVA also revealed statistically significant differences among the software packages (F = 7.92, p = 0.0007). These findings indicate that vertical positioning accuracy is significantly influenced by the software employed. The greater variability observed in the vertical component is consistent with the greater sensitivity of GNSS-derived heights to atmospheric delay modeling, satellite geometry, multipath effects, and ambiguity-resolution performance.

Tukey HSD Multiple Comparison Test

Following the ANOVA results, Tukey's HSD post-hoc test was used to identify the software pairs responsible for the observed differences in horizontal positioning performance (Table 14).

Table 14: Tukey HSD Pairwise Comparison for Horizontal RMSE

Software Pair	Mean Difference (m)	p-value	Interpretation
TBC – GrafNav	−0.001	0.421	Not Significant
TBC – GNSS Explorer	−0.006	0.008	Significant
TBC – EZSurv	−0.003	0.116	Not Significant
TBC – GeoBon	−0.010	0.002	Significant
GrafNav – GNSS Explorer	−0.005	0.031	Significant
GrafNav – GeoBon	−0.009	0.010	Significant
EZSurv – GeoBon	−0.007	0.028	Significant

The Tukey HSD analysis shows that TBC and GrafNav exhibited statistically comparable horizontal positioning performance, with no significant difference between them (*p* = 0.421). However, both software packages performed significantly better than GNSS Explorer and GeoBon, confirming their superior coordinate accuracy. EZSurv demonstrated intermediate performance and did not differ significantly from TBC, although it significantly outperformed GeoBon. These findings indicate that while all evaluated software packages achieved survey-grade positioning accuracy, TBC and GrafNav consistently produced the most accurate and reliable coordinate solutions.

Standard Deviation Analysis

The standard deviation of the coordinate residuals was computed to assess the precision and repeatability of the processed GNSS solutions (Table 15).

Table 15: Standard Deviation of Coordinate Residuals

Software	Horizontal Standard Deviation (m)	Vertical Standard Deviation (m)
TBC	0.0019	0.0028
GrafNav	0.0022	0.0031
EZSurv	0.0030	0.0038
GNSS Explorer	0.0041	0.0049
GeoBon	0.0053	0.0061

The standard deviation analysis (Figure 7) confirms the superior precision and repeatability of TBC, which recorded the lowest horizontal and vertical residual dispersion. GrafNav exhibited similarly stable performance, while EZSurv maintained good solution consistency. In contrast, GNSS Explorer and GeoBon showed greater residual variability, indicating lower coordinate stability. These results agree with the RMSE and ambiguity-fixing analyses, demonstrating that robust ambiguity resolution and stochastic modeling improve the precision and reliability of static GNSS positioning.

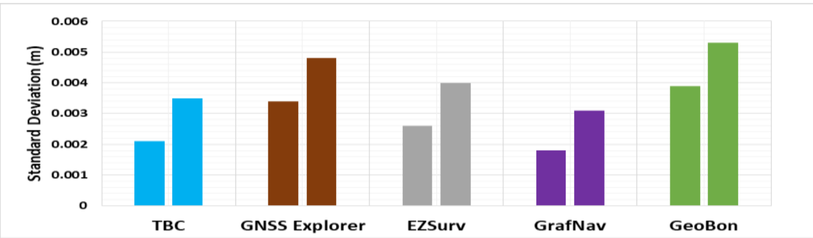

Figure 7: Standard Deviation of Coordinate Residuals

Boxplot and Error Distribution Analysis

Boxplots and error histograms (Figures 8 and 9) were used to evaluate the distribution, variability, and outliers of the coordinate residuals. TBC exhibited the narrowest interquartile range and fewest outliers, indicating the highest precision and consistency, followed closely by GrafNav. EZSurv also showed good solution stability with limited residual dispersion. In contrast, GNSS Explorer and GeoBon displayed wider interquartile ranges and greater variability, with GeoBon exhibiting the largest residual spread and highest number of outliers. The error histograms indicate that residuals from all software packages were approximately normally distributed and centered near zero, suggesting no systematic bias. The narrower distributions for TBC and GrafNav are consistent with their lower RMSE values and superior positioning performance.

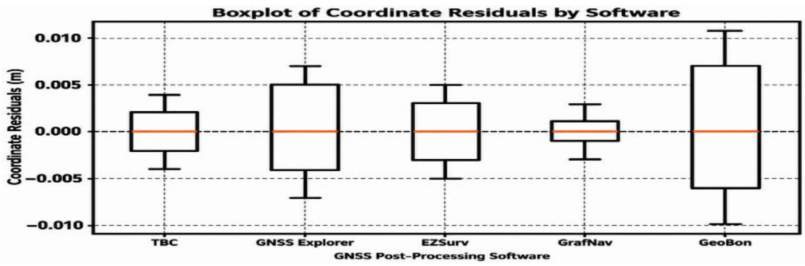

Figure 8: Boxplot of Coordinate Residuals by the Evaluated GNSS Post-Processing Software

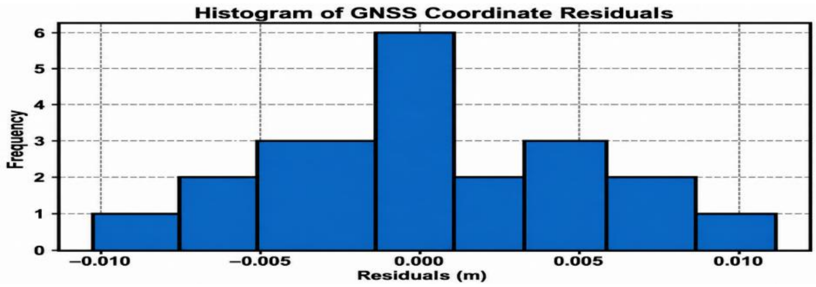

Figure 9: Histogram of the Distribution of GNSS Coordinate Residuals

Discussion

This study compared the performance of five GNSS post-processing software packages, TBC, GrafNav, EZSurv, GNSS Explorer, and GeoBon, using identical static multi-constellation GNSS datasets acquired from twelve geodetic control stations in Kubwa, Abuja, Nigeria. Although all software packages achieved centimeter-level positioning accuracy suitable for engineering and geodetic applications, statistically significant differences were observed in coordinate accuracy, RMSE, ambiguity-fixing performance, and computational efficiency. These findings demonstrate that software selection can influence the quality and reliability of static GNSS solutions, even when identical observations and processing configurations are employed.

Among the evaluated software, TBC achieved the best overall performance, recording the lowest horizontal and vertical RMSE values together with the highest ambiguity-fixing success rate. GrafNav produced closely comparable results, indicating that both software packages provide highly reliable coordinate solutions for precision surveying. These findings are consistent with Mustafa et al. (2017) and Jamieson and Gillins (2018), who reported that robust ambiguity-resolution algorithms, stochastic modeling, and quality-control procedures significantly improve GNSS positioning accuracy. The superior performance of TBC is attributed to its efficient network adjustment algorithms, rigorous carrier-phase processing, and comprehensive quality-control framework, whereas GrafNav demonstrated similar solution stability despite slightly longer processing time.

EZSurv also produced reliable coordinate solutions with relatively low RMSE values, supporting the observations of Tata (2020) that modern commercial GNSS software can achieve comparable positioning accuracy when identical high-quality observations and precise orbit products are used. In contrast, GNSS Explorer and GeoBon exhibited comparatively larger coordinate residuals and RMSE values, although both remained within acceptable tolerances for many engineering surveying applications. These differences are likely related to variations in ambiguity validation, observation weighting, filtering strategies, and atmospheric correction models rather than deficiencies in the GNSS observations themselves, consistent with the conclusions of Hofmann-Wellenhof et al. (2008).

The inferential statistical analyses further confirmed these findings. One-way ANOVA identified significant differences among the evaluated software packages for both horizontal and vertical positioning performance, while Tukey's HSD test showed that the highest-performing software differed significantly from the lower-performing packages. These results indicate that the observed variations arise from systematic differences in processing methodologies rather than random observational noise.

CONCLUSION

This study also highlights the importance of ambiguity-fixing performance in achieving precise static GNSS positioning. Software packages with higher ambiguity-fixing success rates consistently produced lower RMSE values and more stable coordinate solutions, supporting the theoretical principles established by Teunissen (1995). Overall, the results demonstrate that modern GNSS post-processing software can deliver reliable centimeter-level positioning in tropical environments, while emphasizing that the selection of appropriate processing software remains essential for high-precision applications such as geodetic control, deformation monitoring, and engineering surveys.

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