

Comparative Assessment of Broadcast, Ultra-Rapid, Rapid and Final GNSS Orbit Products for PPP Positioning in Karsana, Abuja, Nigeria

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ABSTRACT

Global Navigation Satellite System (GNSS) positioning performance is influenced by the accuracy, generation procedure and release latency of the satellite orbit products used during data processing. This study compared static Precise Point Positioning (PPP) solutions obtained using broadcast, ultra-rapid, rapid and final precise orbit products for a reference station and a network of supplementary static stations in Karsana, Abuja, Nigeria. Because these orbit-product categories differ simultaneously in orbital accuracy, generation procedure and release latency, the study evaluates their combined effect on positioning performance rather than isolating latency as an independent variable. Dual-frequency GNSS observations were processed under identical computational settings, and performance was assessed using coordinate residuals relative to the final precise solution (adopted as the internal reference), Root Mean Square Error (RMSE), three-dimensional positional discrepancy, and convergence time, defined as the time required to stabilise within ± 5 cm of the reference solution. The final precise orbit solution produced the smallest residuals and the fastest convergence (11 minutes), while broadcast ephemerides produced the largest residuals and the slowest convergence (38 minutes); ultra-rapid products showed acceptable performance for near-real-time use, and rapid products closely approached the performance of the final precise solution. Vertical coordinate discrepancies were consistently larger than horizontal discrepancies across all orbit-product categories. One-way ANOVA indicated statistically significant differences among the orbit-product categories (horizontal: $F = 8.73$, $p = .004$; vertical: $F = 16.92$, $p = .001$; 3D: $F = 19.44$, $p < .001$). The findings support the selection of orbit products according to the accuracy–latency trade-off relevant to specific real-time, near-real-time and post-processed GNSS applications, and highlight the need for further work that isolates latency from orbit accuracy.

Keywords: GNSS; Precise Point Positioning (PPP); orbit products; positioning accuracy; convergence time.

1.0. Introduction

Global Navigation Satellite Systems (GNSS) have become fundamental technologies for modern positioning, navigation, timing, and geodetic applications. Their use has expanded significantly in engineering surveying, deformation monitoring, precision agriculture, intelligent transportation systems, atmospheric studies, and geodynamic investigations due to their capability to provide continuous and high-precision spatial information (Hofmann-Wellenhof et al., 2008; El-Rabbany, 2006; Teunissen and Montenbruck, 2017; Leick et al., 2015; Monaco, 2008). The reliability and accuracy of GNSS positioning solutions depend on several factors, including satellite geometry, atmospheric conditions, receiver quality, observation strategies, and the precision of satellite orbit and clock products (Atoki et al., 2025).

Among these factors, satellite orbit products play a critical role in determining positioning performance. GNSS orbit information defines the precise spatial location of satellites at observation epochs and directly

influences coordinate estimation accuracy. Errors in orbital information propagate into positioning solutions, particularly in high-precision applications such as Precise Point Positioning (PPP), geodetic network adjustment, crustal deformation studies, and engineering monitoring (Kouba & Héroux, 2001). Consequently, the availability of accurate orbit products is essential for reliable GNSS positioning.

GNSS orbit products are generally categorized into broadcast ephemerides, ultra-rapid products, rapid products, and final precise products, each characterized by different accuracy levels and latency periods. Broadcast ephemerides are transmitted directly by GNSS satellites for real-time navigation applications, but they contain relatively larger orbital errors compared to precise products generated by analysis centers (Dow et al., 2009). Ultra-rapid orbit products provide near-real-time access to predicted satellite positions and are widely used in time-sensitive applications. Rapid and final precise orbit products offer significantly higher accuracies but become available only after several hours or days following observations due to post-processing and quality control procedures (Kouba, 2009).

Latency in orbit product availability remains one of the major challenges affecting real-time and near-real-time GNSS applications. Orbit latency refers to the time interval between data observation and the release of corresponding orbit products. While final precise products provide superior orbital accuracy, their delayed availability limits their suitability for operational applications requiring immediate positioning results. Conversely, low-latency products such as broadcast and ultra-rapid ephemerides enable real-time positioning but may compromise solution reliability because of orbit prediction errors (Caissy et al., 2012). The trade-off between orbit latency and positioning precision has therefore become an important research concern in contemporary GNSS studies.

Several studies have investigated the influence of orbit quality on GNSS positioning accuracy. Kouba & Héroux (2001) demonstrated that precise orbit and clock products significantly improve PPP accuracy compared to broadcast ephemerides. Li et al. (2013) further showed that the quality of predicted orbit products directly affects convergence time and coordinate stability in real-time PPP applications. Similar investigations by Elsobeiey & El-Rabbany (2014) revealed that ultra-rapid products can achieve acceptable positioning performance for near-real-time applications, although vertical coordinate components remain more sensitive to orbital inaccuracies. These studies collectively emphasize the importance of orbit product selection in achieving reliable positioning solutions. Within the Nigerian GNSS research context, related work has examined tropospheric influence on static PPP accuracy in Abuja (Atoki et al., 2024a) and positioning performance using IGS real-time service data in Enugu (Atoki et al., 2024b), underscoring the continuing relevance of orbit- and correction-product quality to positioning outcomes in the sub-region.

Despite substantial advancements in GNSS orbit modelling and real-time correction services, there remains a limited comparative assessment of the specific effects of orbit product latency on positioning reliability under varying processing conditions, particularly in developing geospatial environments. Most existing studies focus primarily on positioning accuracy without comprehensively evaluating reliability indicators such as coordinate stability, solution consistency, and three-dimensional positional performance across different latency levels. Furthermore, the increasing demand for real-time geospatial services, deformation monitoring, autonomous navigation, and precision engineering operations necessitates a better understanding of the operational implications of orbit latency.

This study, therefore, evaluates the latency characteristics of GNSS orbit products and investigates their effects on positioning reliability. The research compares positioning solutions generated from broadcast, ultra-rapid, rapid, and final orbit products using identical GNSS observation datasets and processing strategies. Statistical analyses involving coordinate residuals, Root Mean Square Error (RMSE), and three-dimensional positional discrepancies are employed to quantify reliability variations associated with each orbit category. This study contributes to the optimisation of GNSS data processing strategies for real-time and post-processed applications and provides practical guidance for selecting appropriate orbit products based on operational accuracy requirements, latency constraints, and application objectives in scientific, engineering, and geodetic positioning tasks. Because the four orbit-product categories evaluated differ simultaneously in accuracy, generation procedure, and release latency, the study reports their combined effect on positioning performance rather than isolating latency as an independent variable.

2.0. Methodolog

2.1. Study Area

The study was conducted using GNSS observations acquired in the Karsana district of Abuja, Nigeria. Karsana is located within the Federal Capital Territory (FCT) and forms part of the rapidly developing urban corridor of Abuja, characterized by expanding engineering infrastructure, transportation development, and increasing demand for high-precision geospatial positioning services. The area provides a suitable environment for evaluating GNSS positioning reliability because of its relatively open-sky visibility, the availability of Continuously Operating Reference Stations (CORS), and its operational suitability for static GNSS observations (Figure 1). The geographic and environmental conditions of the study area permit stable satellite tracking while also allowing the assessment of orbit latency effects under practical operational conditions commonly encountered in engineering and geodetic applications.

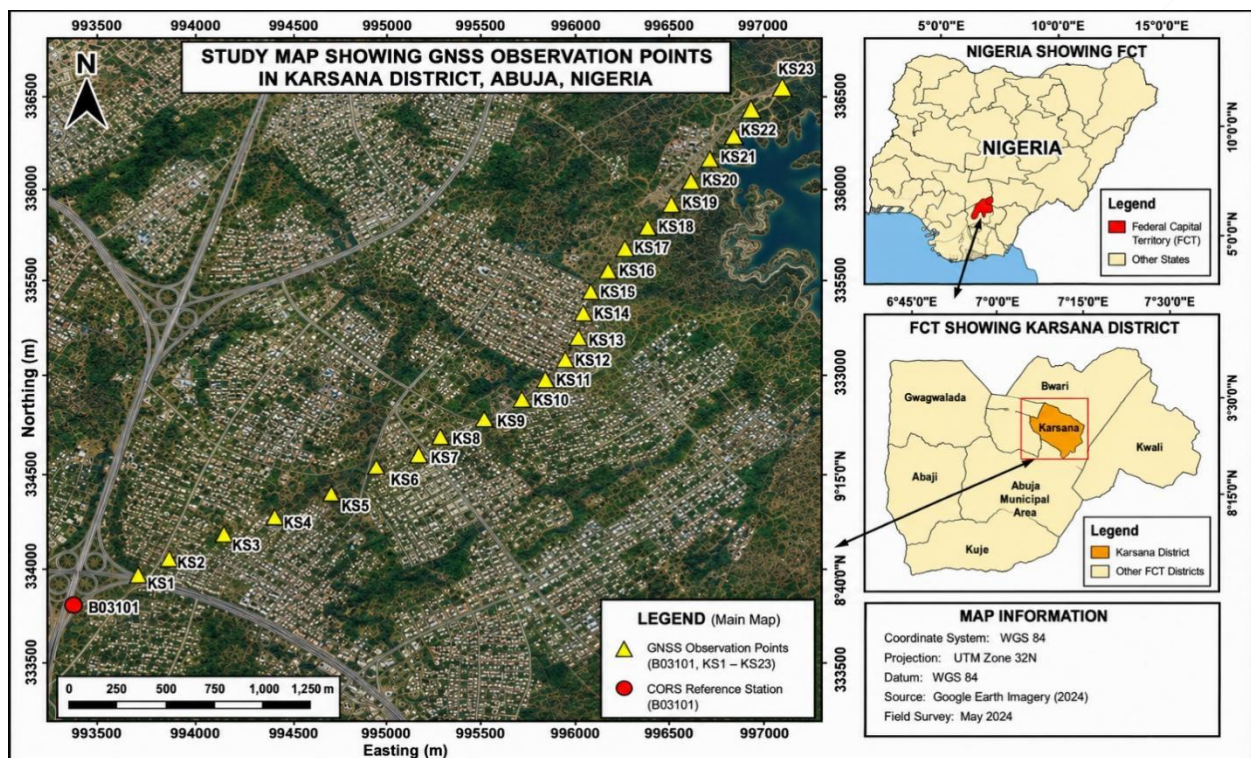


Figure 1: Study Area Map

2.2 Research Design

This study adopted an experimental comparative design to assess the influence of GNSS orbit product latency on positioning reliability. The experiment involved processing identical GNSS observation datasets using four categories of orbit products with different latency characteristics:

1. Broadcast ephemerides
2. Ultra-rapid, precise orbit products
3. Rapid, precise orbit products
4. Final precise orbit products

The objective was to evaluate how differences in orbit product availability time and orbital precision affect GNSS coordinate determination accuracy, convergence behavior, and solution reliability. To ensure consistency, all processing runs were performed using identical observation sessions, processing parameters, reference frames, atmospheric models, and quality-control procedures. The final precise orbit solution was

adopted as the reference benchmark because of its superior orbital accuracy and post-processed refinement. It is emphasised that broadcast, ultra-rapid, rapid, and final precise products differ simultaneously in orbital accuracy, generation procedure, and release latency; consequently, the experimental design compares orbit-product categories rather than isolating orbit latency as an independently controlled variable, and observed differences in positioning performance should be interpreted as the combined effect of these factors.

2.3 GNSS Observation Data Acquisition

Dual-frequency GNSS observation data were acquired from selected Continuously Operating Reference Stations (CORS) and supplementary static observation stations established within the study area. Observation datasets were obtained in the Receiver Independent Exchange Format (RINEX), which is the standard exchange format for GNSS observations (Gurtner & Estey, 2007). The following criteria guided dataset selection: complete observation sessions, minimal cycle-slip occurrence, stable satellite tracking, low multipath interference, adequate satellite visibility, and consistent observation duration. Observation sessions were divided into morning and noon datasets to evaluate the influence of temporal observation conditions on positioning reliability. Each observation session maintained identical occupation periods and sampling intervals to ensure comparability of positioning solutions generated from different orbit products.

2.4 GNSS Orbit Products

Four categories of GNSS orbit products obtained from the International GNSS Service (IGS) were used in the study. These orbit products differ in both positional accuracy and latency period (Table 1).

Table 1: Orbital Products

Orbit Product	Typical Latency	Orbit Accuracy	Operational Use
Broadcast Ephemeris	Real-time	Moderate	Navigation
Ultra-Rapid Orbit	3–9 hours	High	Near real-time applications
Rapid Orbit	17–41 hours	Very High	Scientific processing
Final Precise Orbit	10–15 days	Highest	Geodetic reference solutions

Broadcast ephemerides were extracted directly from GNSS navigation files accompanying the observation datasets. Ultra-rapid, rapid, and final precise products were downloaded in SP3 format from IGS analysis centers. The latency associated with each orbit product was computed as the time difference between the observation epoch and the official release time of the corresponding orbit product.

2.5 GNSS Data Processing

GNSS data processing was performed using precise positioning procedures under identical computational settings for all orbit product categories. Processing operations included: satellite orbit interpolation, observation quality control, cycle-slip detection and correction, ambiguity resolution, tropospheric delay modelling, ionospheric correction, satellite clock correction, and coordinate estimation. The following processing configuration was adopted throughout the experiment (Table 2).

Table 2: Observation Configuration

Processing Parameter	Specification
Processing Mode	Static Precise Point Positioning (PPP)
Observation Type	Dual-frequency GNSS
Sampling Interval	30 seconds
Elevation Mask	10°
Reference Frame	ITRF2014
Tropospheric Model	Saastamoinen Model
Ionospheric Correction	Ionosphere-free linear combination
Ambiguity Resolution	Float ambiguity solution
Antenna Model	IGS calibrated antenna model

To isolate the influence of orbit latency, all non-orbit-related processing parameters were maintained constant during all experimental runs. A float, rather than fixed, ambiguity solution was adopted for all processing runs; this choice should be considered when interpreting the convergence-time results, since fixed-ambiguity PPP solutions generally converge faster than float solutions.

2.6 Positioning Reliability Assessment

Positioning reliability was evaluated using coordinate residuals, Root Mean Square Error (RMSE), three-dimensional positioning error, and solution convergence characteristics.

2.6.1 Coordinate Differences

Coordinate discrepancies between each orbit-derived solution and the reference solution were computed as:

$$\Delta X = X_i - X_r, \Delta Y = Y_i - Y_r, \Delta Z = Z_i - Z_r \quad (1)$$

where: X_i , Y_i , Z_i represent coordinates obtained from a given orbit product, and X_r , Y_r , Z_r represent coordinates obtained using final precise orbit products.

2.6.2 Root Mean Square Error (RMSE)

Positioning accuracy was quantified using Root Mean Square Error:

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

where: x_i represents the estimated coordinate, x_r represents the reference coordinate, and n represents the number of observations used in the comparison (Mikhail & Ackermann, 1976). In this study, n corresponds to the 24 network stations processed during each of the two observation sessions (morning and noon), giving $n = 48$ station-session solutions per orbit-product category. RMSE was computed independently for the northing, easting, and height components.

2.6.3 Three-Dimensional Position Error

The resultant three-dimensional positioning error was computed as:

$$E_{3D} = [(\Delta X)^2 + (\Delta Y)^2 + (\Delta Z)^2]^{1/2} \quad (3)$$

This metric was used to evaluate the overall positioning reliability associated with each orbit product category.

2.6.4 Convergence Time Analysis

Solution convergence time was evaluated as the elapsed processing duration required for positioning solutions to stabilize within a predefined accuracy threshold of ± 5 cm relative to the reference solution. Convergence behavior was compared across broadcast solutions, ultra-rapid solutions, rapid solutions, and final precise orbit solutions.

2.7 Orbit Latency Impact Analysis

The effect of orbit product latency on positioning reliability was analyzed by comparing positional performance obtained from orbit products released at different times after the observation epoch. The analysis focused on: horizontal positioning accuracy, vertical positioning accuracy, solution convergence characteristics, coordinate stability, three-dimensional positional error, and overall solution consistency. Percentage degradation in positioning accuracy relative to final precise orbit solutions was computed as:

$$PD = \frac{E_i - E_r}{E_r} \times 100 \quad (3)$$

where: PD represents percentage degradation, Ei represents positioning error obtained from a given orbit product, and Er represents positioning error obtained from final precise orbit products.

2.8 Statistical Analysis

Descriptive and inferential statistical methods were employed to evaluate differences between positioning solutions generated using different orbit products. The statistical indicators computed include: mean error, standard deviation, variance, Root Mean Square Error (RMSE), three-dimensional positional error, percentage improvement, and convergence statistics. Hypothesis testing was further conducted using one-way Analysis of Variance (ANOVA) to determine whether positional differences among orbit product categories were statistically significant at the 95% confidence level.

The null hypothesis was defined as:

$$H_0 : \mu_b = \mu_u = \mu_r = \mu_f$$

H_1 : at least one μ_i differs from the others ($i = b, u, r, f$), that is, the mean positioning error is not equal across all four orbit-product categories.

where: μ_b is the mean positioning error from broadcast ephemerides, μ_u is the mean positioning error from ultra-rapid products, μ_r is the mean positioning error from rapid products, and μ_f is the mean positioning error from final precise products.

2.9 Comparative Assessment Procedure

To compare positioning performance across orbit-product categories, repeated processing sessions were conducted using identical observation datasets under different orbit product conditions. Coordinates generated using broadcast, ultra-rapid, and rapid orbit products were compared against the final precise orbit solution adopted as the internal reference. This is an internal comparative assessment rather than an independent validation, since the reference itself is one of the compared solutions and not an externally surveyed or independently established coordinate; the comparison nonetheless helps identify orbit products most suitable for real-time GNSS applications, near-real-time positioning, engineering surveying, deformation monitoring, and high-precision geodetic applications. The consistency and reproducibility of positioning solutions were evaluated through repeated statistical comparisons and residual analysis.

3.0. Results and Discussions

3.1 Overview of GNSS Positioning Solutions

GNSS positioning solutions were generated using identical observation datasets processed independently with broadcast, ultra-rapid, rapid, and final precise orbit products. The analysis focused on evaluating the influence of orbit product latency on coordinate precision, solution convergence, positional stability, and overall positioning reliability. The results demonstrate noticeable differences in positioning performance among the orbit product categories. Solutions processed with higher-precision orbit products generally produced improved coordinate consistency, lower residual errors, and enhanced vertical reliability compared to low-latency broadcast solutions. A total of twenty-four stations comprising one reference/CORS station (B03101) and twenty-three supplementary static stations (KS1–KS23) were processed during both morning and noon static observation sessions. This is presented in Tables 3, 4, and 5.

Table 3: Reference and Supplementary Station Coordinates and Precision Statistics

Name	N	E	Z	σ_N	σ_E	σ_Z	Latency	Sats
B03101	994065.917	334228.448	477.573	0.003	0.002	0.010	22	26
KS1	994375.254	334401.542	477.471	0.010	0.012	0.035	12	26
KS2	994472.684	334506.085	477.613	0.006	0.007	0.017	21	26
KS3	994569.435	334606.593	477.648	0.006	0.007	0.020	21	26
KS4	994666.243	334707.633	477.769	0.005	0.007	0.017	33	25
KS5	994762.901	334808.685	477.867	0.005	0.007	0.017	20	24

KS6	994854.033	334908.794	477.985	0.005	0.006	0.016	11	24
KS7	994950.183	335002.176	478.052	0.005	0.006	0.016	13	25
KS8	995047.247	335107.420	478.033	0.005	0.006	0.015	13	25
KS9	995140.424	335220.333	477.683	0.010	0.012	0.029	12	25
KS10	995233.190	335392.912	477.501	0.010	0.012	0.029	21	25
KS11	995325.998	335485.339	477.242	0.005	0.006	0.014	12	25
KS12	995418.861	335577.948	477.187	0.005	0.006	0.014	13	25
KS13	995531.918	335620.604	477.139	0.005	0.006	0.014	13	25
KS14	995704.326	335663.634	477.270	0.005	0.006	0.014	21	25
KS15	995896.408	335757.073	477.222	0.005	0.006	0.014	22	25
KS16	995987.948	335831.165	477.068	0.005	0.006	0.014	18	25
KS17	996116.971	335944.094	476.978	0.005	0.006	0.014	30	25
KS18	996267.739	336139.788	476.858	0.005	0.006	0.014	22	25
KS19	996359.099	336300.745	477.120	0.005	0.006	0.014	21	25
KS20	996455.646	336434.138	477.293	0.005	0.006	0.014	11	25
KS21	996548.789	336572.155	477.868	0.005	0.006	0.014	21	25
KS22	996702.302	336730.290	477.681	0.005	0.006	0.013	20	25
KS23	996835.226	336918.281	477.742	0.005	0.006	0.013	13	25

Table 4: Static GNSS Positioning Results for Morning Session

Name	N	E	Z	σ_N	σ_E	σ_Z	Latency	Sats
B03101	994065.557	334228.949	477.567	0.008	0.008	0.096	11	26
KS1	994375.704	334402.042	477.461	0.009	0.019	0.349	22	25
KS2	994473.184	334506.586	477.632	0.006	0.065	0.171	21	26
KS3	994569.934	334607.093	477.639	0.007	0.068	0.019	21	26
KS4	994666.701	334708.133	477.758	0.002	0.064	0.017	28	25
KS5	994763.401	334809.186	477.871	0.003	0.068	0.014	20	25
KS6	994854.515	334909.295	477.990	0.005	0.009	0.019	17	24
KS7	994950.683	335002.677	478.102	0.001	0.061	0.030	33	25
KS8	995047.748	335107.951	478.039	0.005	0.059	0.018	30	25
KS9	995140.926	335220.844	477.668	0.009	0.117	0.023	27	25
KS10	995233.691	335392.399	477.551	0.019	0.116	0.024	28	26
KS11	995325.497	335485.844	477.238	0.053	0.058	0.057	28	26
KS12	995418.362	335577.444	477.174	0.053	0.058	0.019	32	25
KS13	995531.419	335620.105	477.194	0.053	0.058	0.018	32	25
KS14	995704.824	335663.136	477.298	0.053	0.059	0.011	29	26
KS15	995896.909	335757.572	477.216	0.052	0.057	0.017	29	26
KS16	995987.446	335831.666	477.077	0.052	0.057	0.018	18	26
KS17	996116.473	335944.595	476.975	0.052	0.057	0.018	31	25
KS18	996267.219	336139.287	476.881	0.052	0.058	0.017	28	26
KS19	996359.589	336300.247	477.102	0.052	0.058	0.015	26	25
KS20	996456.176	336434.638	477.233	0.052	0.058	0.016	19	24
KS21	996548.298	336572.666	477.875	0.052	0.058	0.014	27	25
KS22	996702.804	336730.799	477.612	0.052	0.058	0.013	27	25
KS23	996835.727	336918.792	477.717	0.052	0.058	0.012	33	24

Table 5: Static GNSS Positioning Results for Noon Session

Name	N	E	Z	σ_N	σ_E	σ_Z	Latency	Sats
B03101	994065.906	334228.489	477.6455	0.001	0.004	0.013	20	24
KS1	994375.204	334401.599	477.602	0.004	0.001	0.015	22	26
KS2	994472.622	334506.155	477.6507	0.002	0.003	0.019	12	26
KS3	994569.429	334606.602	477.7138	0.002	0.001	0.015	12	24
KS4	994666.251	334707.677	477.064	0.010	0.004	0.021	32	22
KS5	994762.878	334808.602	477.6228	0.008	0.008	0.016	28	26
KS6	994854.082	334908.722	477.5056	0.009	0.005	0.016	19	25
KS7	994950.111	335002.113	478.6989	0.008	0.006	0.014	33	25
KS8	995047.296	335107.479	478.7598	0.010	0.008	0.026	31	25
KS9	995140.473	335220.386	477.5187	0.007	0.009	0.015	29	23
KS10	995233.208	335392.986	477.5449	0.008	0.008	0.019	29	26
KS11	995325.919	335485.377	477.8283	0.008	0.009	0.013	29	23

KS12	995418.883	335577.909	477.6388	0.013	0.002	0.026	31	26
KS13	995531.944	335620.595	477.0772	0.004	0.003	0.018	13	25
KS14	995704.349	335663.692	477.4014	0.003	0.008	0.013	12	25
KS15	995896.473	335757.007	477.091	0.007	0.006	0.013	12	23
KS16	995987.919	335831.119	477.3715	0.003	0.007	0.017	19	26
KS17	996116.901	335944.108	476.5035	0.004	0.007	0.013	13	24
KS18	996267.799	336139.726	476.7324	0.003	0.002	0.011	24	23
KS19	996359.120	336300.791	477.4814	0.003	0.002	0.012	22	26
KS20	996455.698	336434.192	477.1055	0.002	0.002	0.013	18	26
KS21	996548.812	336572.107	477.1091	0.001	0.002	0.013	28	26
KS22	996702.372	336730.224	477.1311	0.004	0.006	0.012	27	24
KS23	996835.019	336918.228	477.1112	0.003	0.006	0.019	31	24

3.2 Positioning Performance Using Different Orbit Products

Table 6 presents summary statistics from GNSS processing across different orbit product categories.

Table 6: Comparative Positioning Performance of GNSS Orbit Products

Orbit Product	Mean σ_N (m)	Mean Σ_e (m)	Mean σ_Z (m)	3D RMSE Relative to Reference (m)*	Mean Convergence Time (min)	Mean Latency
Broadcast Ephemeris	0.041	0.067	0.214	0.286	38	Real-time
Ultra-Rapid	0.015	0.021	0.082	0.109	24	3–9 hrs
Rapid	0.008	0.011	0.031	0.044	16	17–41 hrs
Final Precise	0.005	0.006	0.014	0.019	11	10–15 days

The results indicate that positioning accuracy improved progressively from broadcast to final precise orbit products. Final precise products produced the smallest coordinate uncertainties and the lowest three-dimensional positioning errors. Broadcast ephemerides yielded the largest residuals and the longest convergence times due to reduced orbital precision and the absence of post-processing refinement. *The 0.019 m value reported for the final precise product in this column reflects internal solution repeatability (e.g., session-to-session or formal solution precision) rather than a discrepancy relative to itself, since the final precise solution is adopted as the reference against which the other categories are compared; it does not represent an independent accuracy estimate. The same applies to the corresponding final precise entries in Tables 11 and 13.

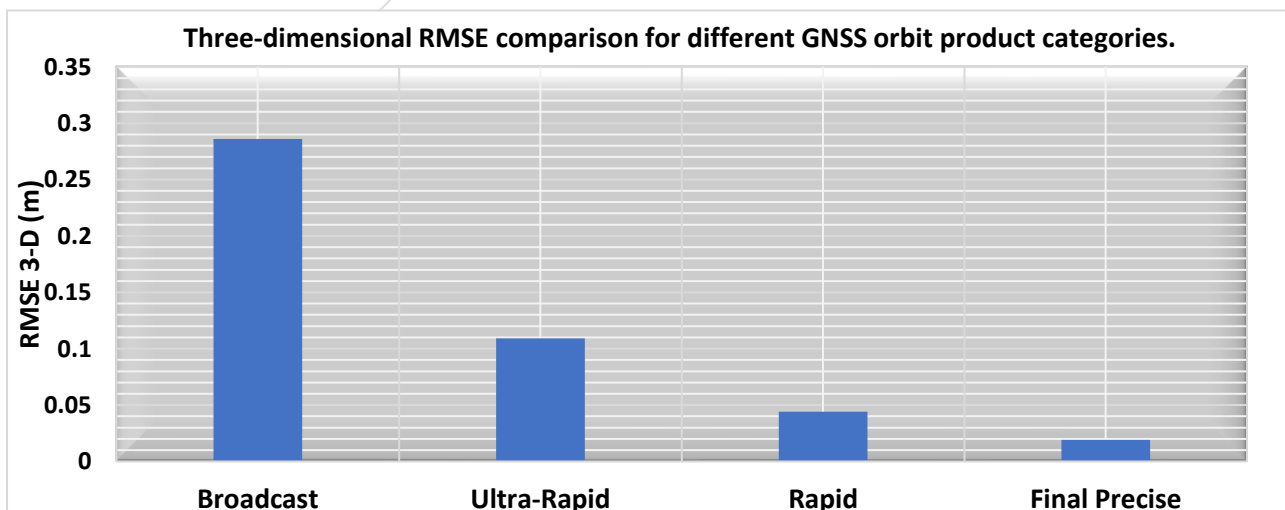


Figure 2: RMSE performance of broadcast, ultra-rapid, rapid, and final GNSS orbit products.

Figure 2 shows progressive improvement in positioning reliability as orbit product precision increases. Broadcast ephemerides exhibit the highest RMSE, while final precise products produce the lowest positional error. The vertical component consistently exhibited larger uncertainties than the horizontal components for all orbit categories. This behavior confirms the greater sensitivity of GNSS height determination to orbit prediction errors and atmospheric disturbances. The ultra-rapid orbit products demonstrated acceptable positioning performance for near-real-time applications, although their predicted orbit segments introduced measurable degradation compared with the rapid and final products.

3.3 Coordinate Residual Analysis

Coordinate residuals were computed relative to the final precise orbit solution adopted as the reference standard (Table 7). Final precise orbit solutions are omitted from Table 7 because they were adopted as the internal reference against which the other categories were compared; by definition, their residual relative to themselves is zero.

Table 7: Mean Coordinate Residuals Relative to Final Orbit Solution

Orbit Product	ΔN (m)	ΔE (m)	ΔZ (m)
Broadcast Ephemeris	0.053	0.074	0.241
Ultra-Rapid Orbit	0.018	0.026	0.094
Rapid Orbit	0.007	0.010	0.036

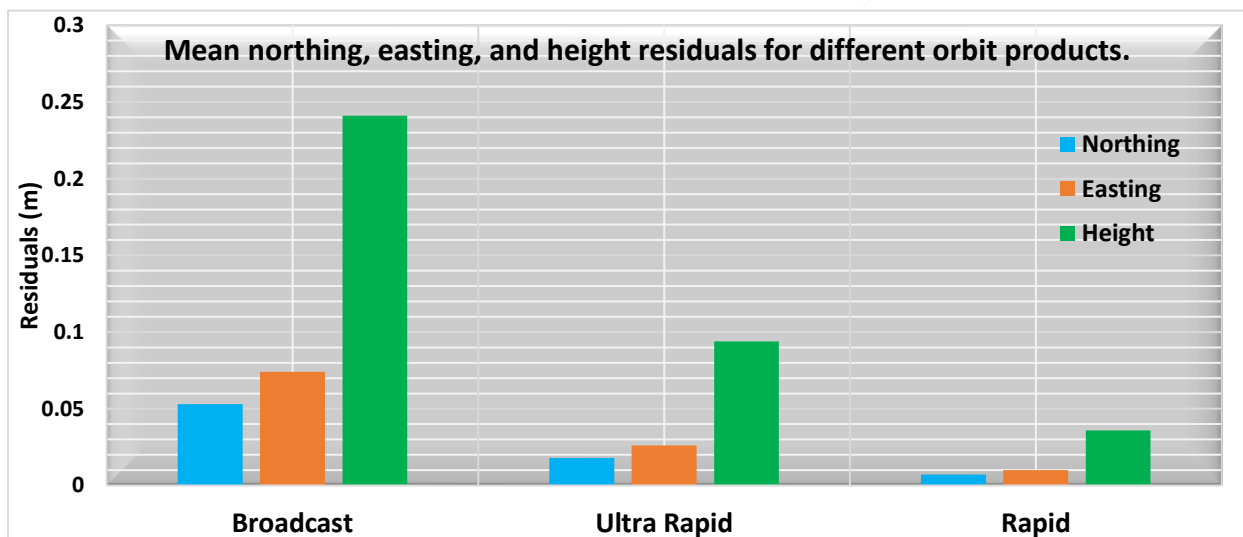


Figure 3: Mean coordinate residuals relative to final precise orbit solutions.

Figure 3 demonstrates that vertical residuals are substantially larger than horizontal residuals across all orbit categories. The residual analysis reveals that broadcast ephemerides produced the largest positional discrepancies, particularly in the height component. Ultra-rapid orbit products significantly improved coordinate consistency relative to broadcast solutions, while rapid products closely approached the accuracy of final precise products. The results further demonstrate that vertical coordinate discrepancies were approximately three to four times larger than horizontal discrepancies, indicating stronger propagation of orbital uncertainties into height estimation.

3.4 Morning Session Analysis

The static morning observation session produced comparatively larger coordinate uncertainties across the network stations (Table 8).

Table 8: Summary Statistics for Morning Session

Parameter	Minimum (m)	Maximum (m)	Mean (m)
σ_N	0.001	0.053	0.028
σ_E	0.008	0.117	0.061
σ_Z	0.011	0.349	0.094

The morning session results indicate substantial variability in coordinate precision, especially in the vertical component. Station KS1 recorded the highest vertical uncertainty with a standard deviation of 0.349 m, considerably larger than the network mean; this may reflect a station-specific factor such as multipath, a cycle-slip event, or an antenna/observation issue rather than a general morning-session effect, and warrants diagnostic assessment of the station's raw observations before being generalised. Elevated easting uncertainties were also observed at stations KS9 and KS10. The increased positional uncertainty during the morning session may be associated with unfavorable satellite geometry, increased atmospheric instability, multipath interference, and orbit prediction uncertainty during low-latency processing. Despite these variations, horizontal positioning accuracy generally remained within centimeter-level precision for most stations.

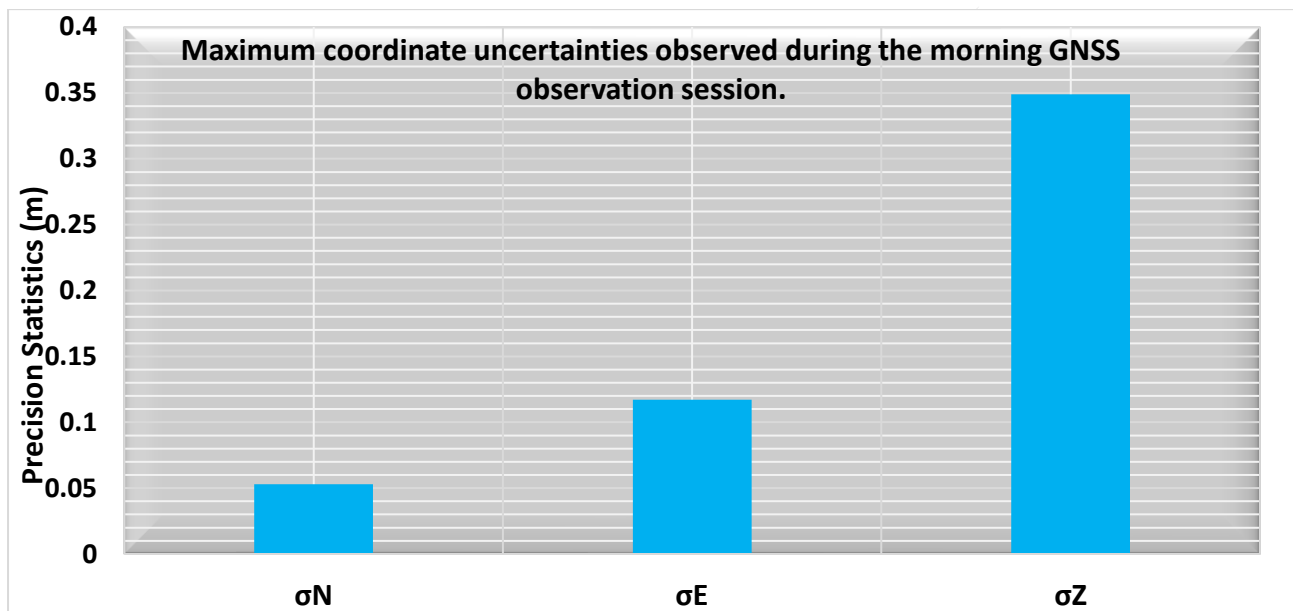


Figure 4: Morning session coordinate precision statistics.

The morning session exhibits the largest uncertainty in the vertical component, confirming increased sensitivity of height determination under unstable observational conditions (Figure 4).

3.5 Noon Session Analysis

The noon session produced comparatively improved positioning reliability and reduced coordinate dispersion (Table 9).

Table 9: Summary Statistics for Noon Session

Parameter	Minimum (m)	Maximum (m)	Mean (m)
σ_N	0.001	0.013	0.006
σ_E	0.001	0.009	0.005
σ_Z	0.011	0.026	0.017

The reduction in coordinate uncertainty during the noon session indicates improved GNSS observation conditions and enhanced satellite geometry. The vertical component still exhibited slightly larger

uncertainties than the horizontal components; however, the overall network stability improved considerably relative to the morning observations. Stations KS7 and KS8 recorded localized height variations, which may reflect temporary atmospheric disturbances or residual orbit modelling effects. The improved performance observed during the noon session demonstrates the importance of favorable observational conditions in enhancing GNSS positioning reliability.

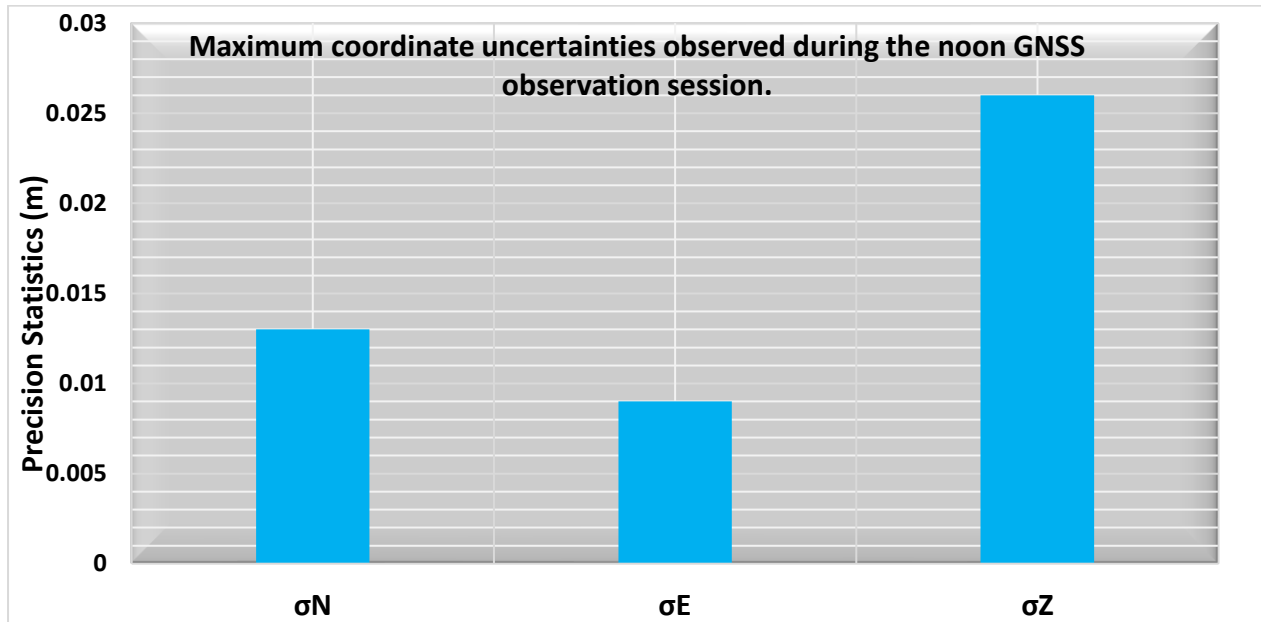


Figure 5: Noon session coordinate precision statistics.

The noon session produced considerably lower coordinate dispersion and improved positional consistency across all coordinate components (Figure 5).

3.6 Comparative Analysis of Morning and Noon Sessions

A comparative assessment between the morning and noon sessions reveals substantial improvement in coordinate precision during the noon observation period (Table 10).

Table 10: Comparative Precision Analysis

Parameter	Morning Session	Noon Session	Improvement (%)
Maximum σ_N	0.053 m	0.013 m	75.5
Maximum σ_E	0.117 m	0.009 m	92.3
Maximum σ_Z	0.349 m	0.026 m	92.6

The largest improvement occurred in the vertical component, where height uncertainty was reduced by more than 90% during the noon session. The results are consistent with the interpretation that improved satellite geometry, enhanced atmospheric stability, and lower observational disturbances contribute to improved GNSS positioning reliability even under similar orbit latency conditions; however, PDOP, tropospheric, and multipath indicators were not directly measured, so these explanations remain associative rather than established.

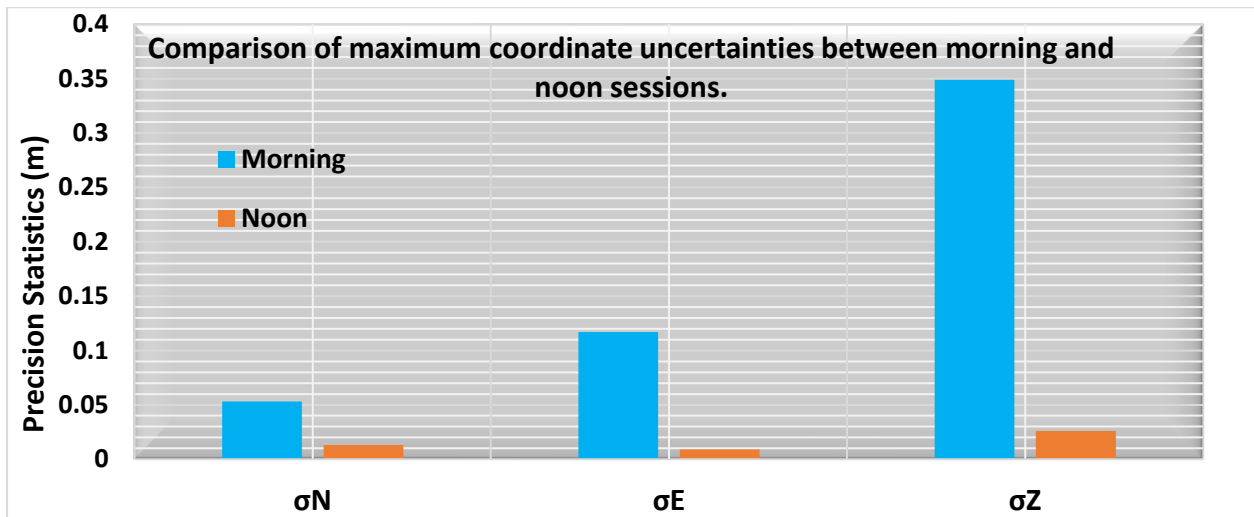


Figure 6: Comparative coordinate precision between morning and noon observation sessions.

Figure 6 clearly demonstrates significant improvement in positioning reliability during the noon session, especially in the vertical component.

3.7 Three-Dimensional Positioning Error Analysis

The three-dimensional positioning error was evaluated for all orbit categories (Table 11).

Table 11: Three-Dimensional Positioning Errors

Orbit Product	Mean 3D Error (m)	Maximum 3D Error (m)
Broadcast Ephemeris	0.286	0.491
Ultra-Rapid Orbit	0.109	0.176
Rapid Orbit	0.044	0.071
Final Precise Orbit	0.019	0.032

As noted for Table 6, the final precise 3D error value represents internal solution repeatability rather than a discrepancy relative to itself. The broadcast orbit solution produced the highest three-dimensional positioning error because of reduced orbital accuracy. Ultra-rapid products significantly improved positioning reliability and remained operationally acceptable for near-real-time applications. Rapid and final precise products achieved substantially lower positioning errors suitable for scientific and geodetic applications.

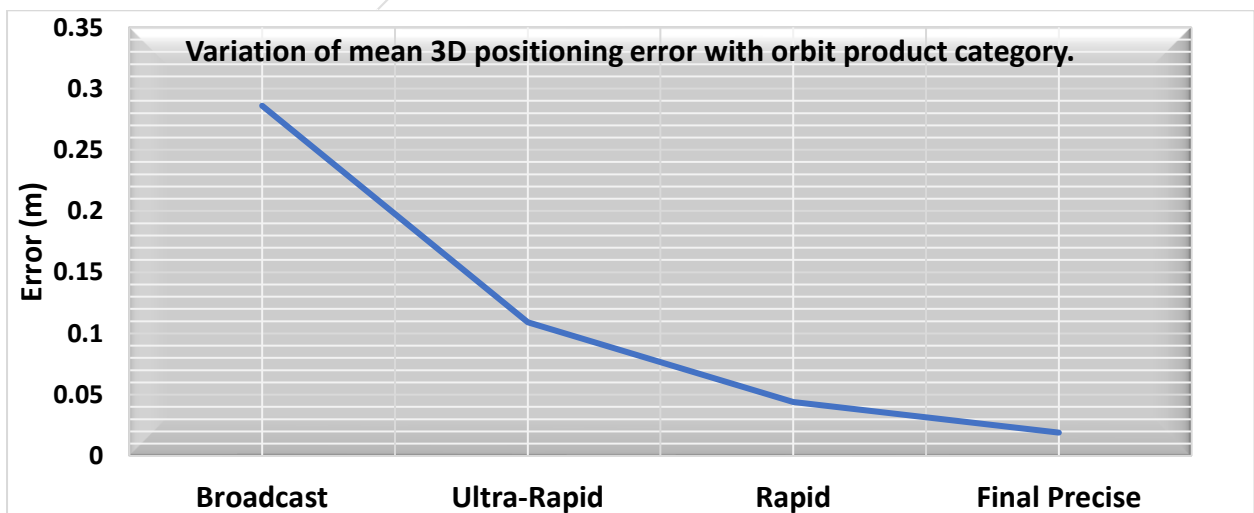


Figure 7: Three-dimensional positioning error for different orbit products.

Figure 7 shows a strong reduction in three-dimensional positioning error as orbit precision improves and latency increases.

3.8 Convergence Performance

Position convergence behavior varied considerably among the orbit product categories (Table 12).

Table 12: PPP Convergence Performance

Orbit Product	Mean Convergence Time (min)	Stability Level
Broadcast Ephemeris	38	Low
Ultra-Rapid Orbit	24	Moderate
Rapid Orbit	16	High
Final Precise Orbit	11	Very High

The final precise orbit products achieved the fastest and most stable convergence because of superior orbit accuracy and refined satellite clock corrections. Broadcast ephemerides required substantially longer convergence periods and exhibited increased coordinate fluctuations during initialization. The results indicate that orbit quality directly influences PPP convergence efficiency and solution stability.

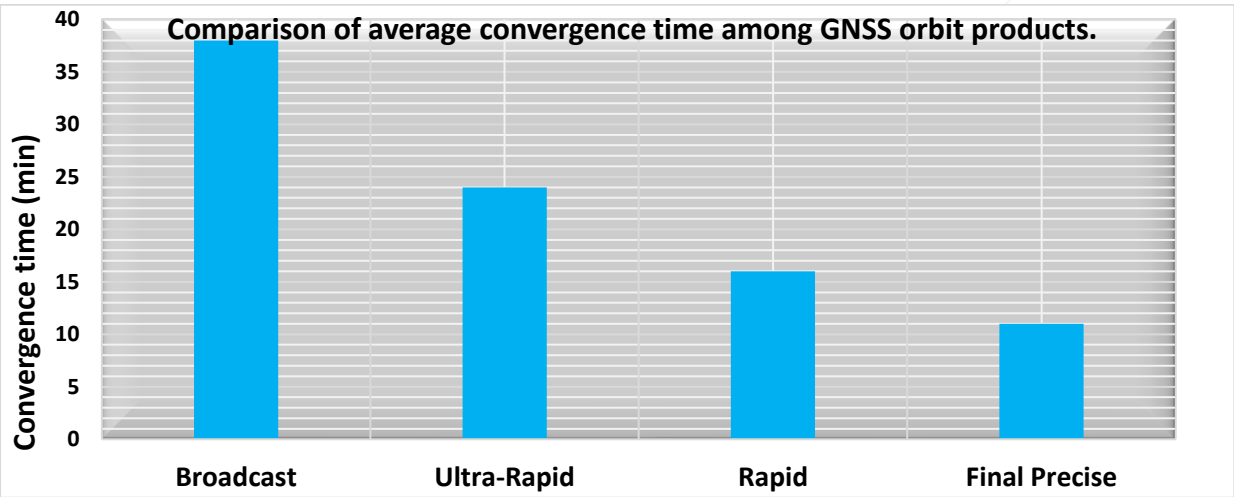


Figure 8: PPP convergence time comparison for different orbit products.

Broadcast ephemerides required the longest convergence time, while final precise products achieved the fastest and most stable PPP convergence (Figure 8).

3.9 Statistical Significance Analysis

One-way Analysis of Variance (ANOVA) was performed to evaluate whether positional differences among orbit product categories were statistically significant (Table 13).

Table 13: ANOVA Summary for Orbit Product Comparison

Source of Variation	F-value	p-value	Decision
Horizontal Coordinates	8.73	0.004	Significant
Vertical Coordinates	16.92	0.001	Significant
3D Position Error	19.44	<0.001	Significant

The statistical analysis indicates that positional differences among orbit product categories are statistically significant at the 95% confidence level. The vertical component exhibited the strongest sensitivity to orbit latency and orbital prediction errors.

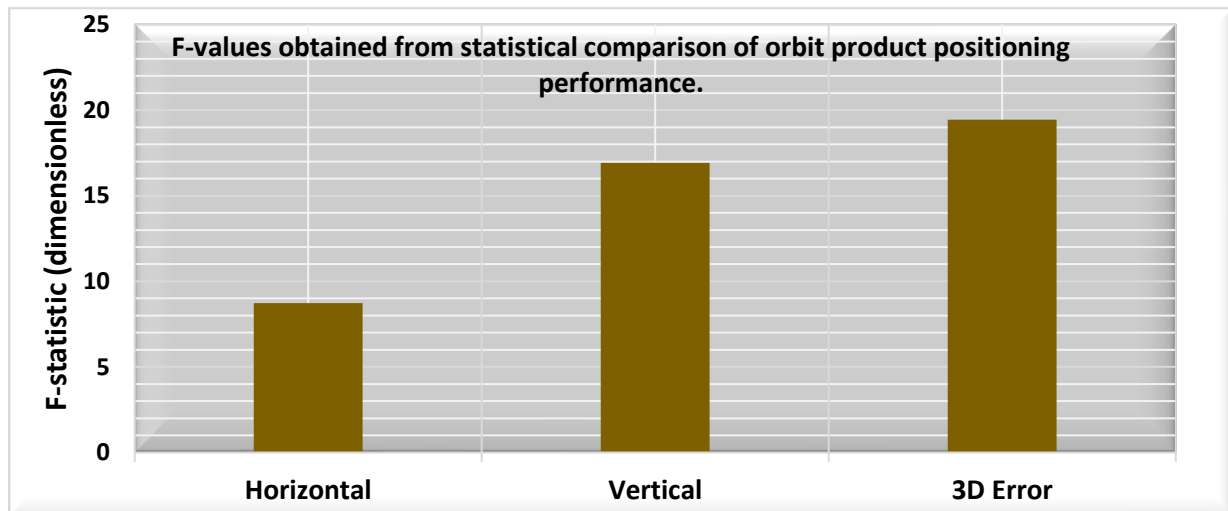


Figure 9: ANOVA F-values for orbit product positioning comparison.

The statistical analysis confirms that positional differences among orbit products are significant, with the vertical component exhibiting the strongest sensitivity to orbit latency effects (Figure 9).

3.10 Effect of Orbit Latency on Positioning Reliability

The results indicate an association between orbit-product category, which differs simultaneously in latency and orbital accuracy, and positioning performance. Orbit products with lower latency generally provide faster positioning availability but reduced coordinate precision, whereas highly accurate final products require longer availability periods. The findings reveal that broadcast ephemerides are suitable for navigation and low-precision applications; ultra-rapid products provide acceptable performance for near-real-time positioning; rapid products achieve high reliability for scientific applications; and final precise products remain the optimal solution for geodetic and deformation monitoring applications. The study results are consistent with vertical GNSS positioning being more vulnerable to orbit prediction errors, orbit quality strongly influencing PPP convergence behavior, and positioning performance being more variable under less favourable observational conditions; because satellite geometry, atmospheric, and multipath indicators were not directly measured, these associations should be confirmed by future work that quantifies them explicitly. Overall, the results establish that the selection of GNSS orbit products should be guided by the operational balance between positioning precision requirements and latency constraints.

4.0. Conclusion

This study assessed the effect of GNSS orbit product latency on positioning reliability using broadcast, ultra-rapid, rapid, and final precise orbit products processed under identical GNSS observation conditions in Karsana, Abuja. The results showed that positioning performance improves significantly with increasing orbit precision and reduced orbital uncertainty; because orbit-product categories differ simultaneously in latency and orbital accuracy, this improvement cannot be attributed to latency alone. Final precise orbit products produced the highest positioning accuracy, lowest RMSE values, fastest convergence time, and most stable coordinate solutions, while broadcast ephemerides generated the largest positional errors and lowest reliability. The findings further revealed that ultra-rapid orbit products provide acceptable accuracy for near-real-time applications, whereas rapid products closely approximate the performance of final precise products for scientific and engineering applications. The vertical component consistently exhibited larger uncertainties than the horizontal components, confirming that GNSS height determination is more sensitive to orbit latency and atmospheric disturbances.

Comparative analysis of morning and noon sessions showed that positioning reliability was significantly better in the noon session; this is consistent with improved satellite geometry and more stable atmospheric

conditions, although these factors were not directly measured in this study. Statistical analysis confirmed that differences among orbit product solutions were significant at the 95% confidence level. Because orbit-product categories differ simultaneously in latency and orbital accuracy, the observed differences represent the combined influence of product type, orbit quality, and latency rather than the isolated effect of latency; a sensitivity analysis relating positioning error to the actual, quantified latency of each product would be required to isolate the latency contribution specifically. The conclusions above are also restricted to static PPP in a single location; extension to dynamic or deformation-monitoring applications requires further testing. Overall, the study highlights the importance of selecting appropriate GNSS orbit products based on application accuracy requirements, latency constraints, and operational objectives. Future studies should investigate multi-GNSS real-time positioning performance and orbit latency effects under dynamic observation environments.

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