

Investigation of GLONASS and Galileo Hybrid Operation for Improved Positioning Precision in Nigeria

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ABSTRACT

Global Navigation Satellite Systems provide positioning, navigation and timing services, but standalone performance in equatorial Nigeria can be affected by satellite geometry, multipath and ionospheric variability. This study compared GLONASS-only, Galileo-only and combined GLONASS-Galileo processing at the LAUTECH GNSS Laboratory, Ogbomoso, Nigeria (8.170544°N, 4.268928°E; 403.411 m ellipsoidal height). A u-blox ZED-F9P receiver tracked GLONASS L1OF/L2OF and Galileo E1/E5b during 24-hour sessions at 4 Hz in May, June and August 2025. RTKPOST used standalone single-point positioning, broadcast ephemerides and ionospheric corrections, the Saastamoinen tropospheric model and a 15° elevation mask; carrier-phase ambiguity resolution was not applied. Valid-day coverage varied by metric. Daily NSV used 14, 13 and 14 paired days in May, June and August, while visibility duration used 14, 13 and 13 days. Galileo had higher daily mean NSV than GLONASS in each month (paired Wilcoxon $p=0.00024$), and this ordering remained when NSV was restricted to the 12 calendar days common to all months. Galileo E5b also had higher monthly hourly mean C/N₀ than GLONASS L2OF. Daily latitude, longitude and altitude standard deviations were lower for Galileo than GLONASS in every month (all paired $p \leq 0.00012$). The 2DRMS, CEP, SEP and MRSE curves were lowest for the combined solution, but these quantities describe scatter around the daily mean and therefore measure precision rather than absolute accuracy. Because the retained thesis contained the containment results only as a plotted series without a traceable dated numerical table, that comparison is treated as descriptive. The results support improved repeatability from combined processing at this site, subject to the unequal standalone signal structures and the limits of the retained data.

Keywords: GLONASS; Galileo; multi-constellation GNSS; carrier-to-noise-density ratio; satellite visibility; positioning precision; Nigeria

INTRODUCTION

Global Navigation Satellite Systems (GNSS) are satellite constellations that provide position, navigation and timing services. The principal global systems are GPS, GLONASS, Galileo and BeiDou. Although each system can provide an independent position fix, modern receivers increasingly combine observations from

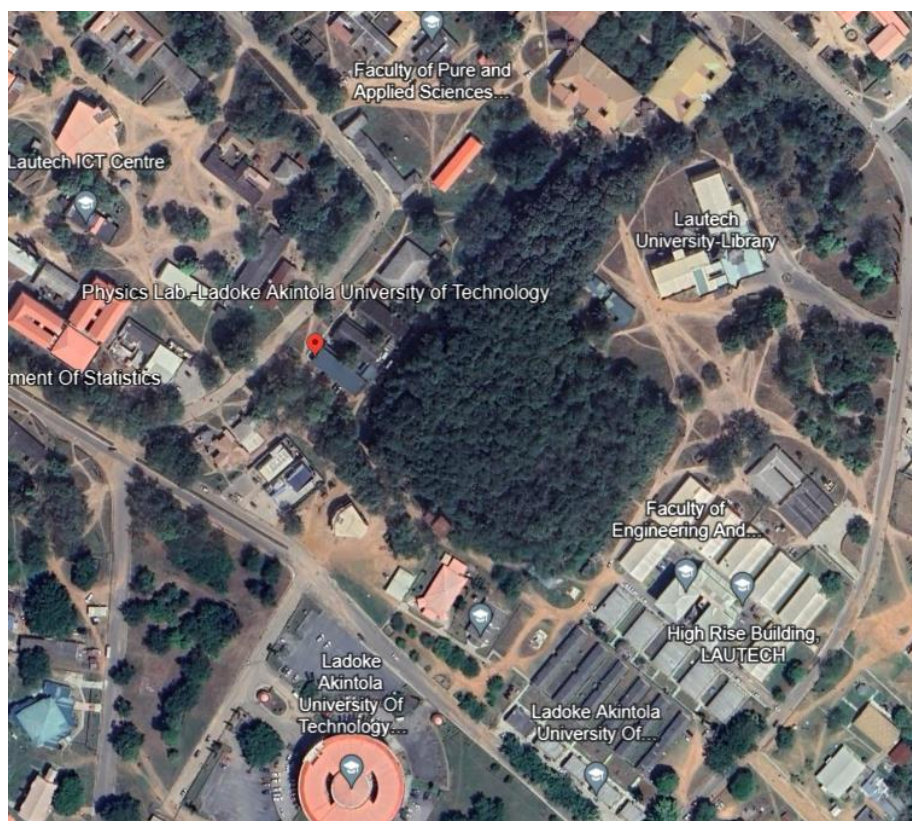
several constellations to increase the number of usable satellites and improve their spatial distribution (Adewumi and Azeez, 2021; Montenbruck et al., 2017). These benefits matter where a single constellation has few satellites above the elevation mask or an unfavourable geometry.

GLONASS and Galileo differ in orbital design and signal structure. GLONASS has historically used frequency-division multiple access, whereas Galileo provides interoperable civilian signals on several frequencies. Their differences can be useful in a combined solution because a weakness in the geometry or tracking of one constellation may be offset by satellites from the other. Multi-GNSS work has shown that greater satellite availability can shorten convergence time and maintain a position solution under restrictive elevation masks (Chen et al., 2021). Reviews of multi-GNSS development similarly identify availability, redundancy and geometry as the main reasons for integration (Jin et al., 2022).

Nigeria lies in a low-latitude region where ionospheric variability can affect GNSS observations. Local performance can also be shaped by the receiver, antenna environment, multipath and the satellites visible at a particular time. Results obtained in Europe or at higher latitudes therefore do not fully describe the operating conditions at a Nigerian site. Recent work at the LAUTECH GNSS Laboratory showed that a compact u-blox ZED-F9P can support precise processing in this environment (Adewumi et al., 2025), but a field comparison focused on GLONASS, Galileo and their combined solution remained limited.

This study investigated whether combined GLONASS-Galileo processing improves service continuity and position-solution quality at a fixed site in Ogbomoso. The objectives were to compare C/N₀, satellite visibility and visibility duration; examine coordinate and elevation-angle variation; and evaluate GLONASS-only, Galileo-only and hybrid solutions using two-dimensional and three-dimensional containment metrics.

Figure 1. LAUTECH GNSS Laboratory study site in Ogbomoso, Nigeria (8.170544°N, 4.268928°E).



Related Work and Research Gap

The International GNSS Service Multi-GNSS Experiment established the data and product infrastructure needed to analyse several navigation systems consistently (Montenbruck et al., 2017). Using multi-system

data, Chen et al. (2021) found that a five-system PPP solution had the shortest mean convergence time in their comparison and retained useful positioning performance when a GPS-only solution failed at a high elevation cut-off. The scale and processing mode differ from the present single-station experiment, but the work demonstrates the geometry and availability gains that motivate constellation integration.

Constellation pairing has also been tested in regional settings. Mahato et al. (2023) combined GLONASS and NavIC observations in India and reported improved continuity and performance relative to standalone operation. Jin et al. (2022) reviewed a wider set of multi-GNSS uses and found that modern multi-frequency, multi-constellation observations support both positioning and Earth-observation applications. These studies establish the general value of hybrid operation, but their regional constellations, latitude and receiver environments are different from a GLONASS-Galileo pair observed in south-western Nigeria. Low-cost receiver performance is directly relevant to adoption in settings where geodetic receivers are difficult to obtain. Adewumi et al. (2025) used the ZED-F9P at the same laboratory and reported that precise point processing could achieve sub-centimetre horizontal results on selected days under favourable conditions. The present study addresses a different question. It tests the operational complementarity of GLONASS and Galileo using signal strength, satellite count, availability, elevation, coordinate scatter and containment metrics over three months. This combination of metrics and the Nigerian low-latitude setting defines the paper's empirical contribution.

MATERIALS AND METHODS

Study Site, Equipment and Observation Schedule

Observations were collected at the LAUTECH GNSS Laboratory within the Department of Pure and Applied Physics complex, Ogbomoso, Oyo State. The fixed reference location was 8.170544°N, 4.268928°E at an ellipsoidal height of 403.411 m. The multi-band antenna was mounted with an open view of the sky and connected by a 50 ohm coaxial cable to a u-blox ZED-F9P dual-frequency receiver. The receiver was configured for GLONASS L1OF and L2OF and Galileo E1B/C and E5b I/Q tracking. A laptop running u-center recorded the raw receiver stream, while an inverter and 12 V battery supported continuous operation. The nominal schedule comprised 24-hour sessions sampled at 4 Hz during 1-15 May, 1-15 June and 1-14 August 2025. Table 2 reports the exact coverage that could be verified. A missing day was treated as unavailable rather than as a zero observation. Comparisons between constellations within each metric used the same retained days. Comparisons between months used all available days and were checked for NSV on the calendar days common to all three months.

Table 1. Observation and processing configuration

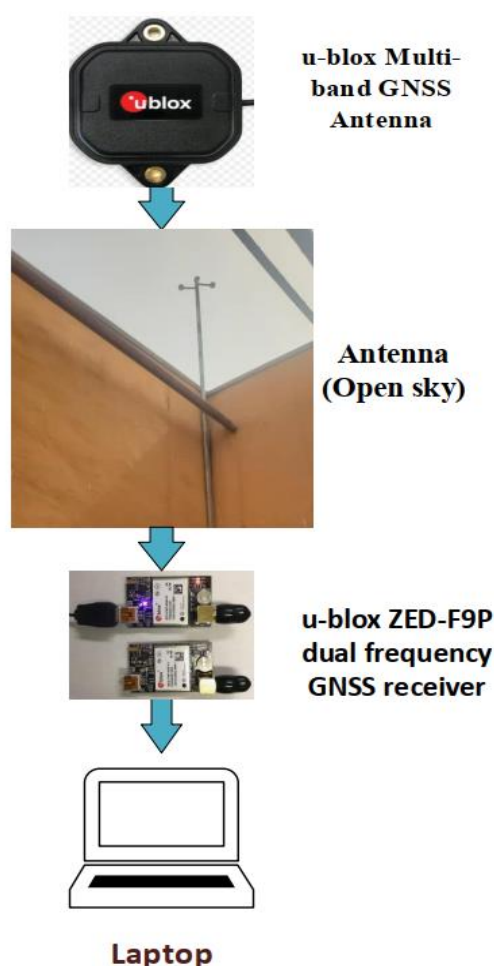
Item	Specification
Study site	LAUTECH GNSS Laboratory, Ogbomoso, Nigeria
Reference coordinate	8.170544°N, 4.268928°E; 403.411 m ellipsoidal height
Receiver and antenna	u-blox ZED-F9P dual-frequency receiver with multi-band active antenna
Signals	GLONASS L1OF/L2OF; Galileo E1B/C and E5b I/Q
Sampling and session	4 Hz; nominal 24-hour daily observation
Observation periods	May and June 2025, nominally 15 days each; August 2025, nominally 14 days
RTKPOST mode	Standalone single-point positioning; no base-station input; ambiguity resolution not applied
Elevation mask	15°
Ionosphere and ephemeris	Broadcast model and broadcast navigation ephemerides
Troposphere and datum	Saastamoinen model; WGS 84

Solution modes	GLONASS-only, Galileo-only and combined GLONASS-Galileo
Software	u-center, RTKLIB/RTKPOST, MATLAB and Tec-Suite

Table 2. Valid observation days retained for each metric

Metric	May-25	Jun-25	Aug-25
Galileo E1/E5b C/N ₀	14: 1-9, 11-15	3/15/2026 14:01	14: 1-14
GLONASS L1OF/L2OF C/N ₀	12: 1-8, 11-13, 15	3/15/2026 14:01	14: 1-14
NSV	14: 1-9, 11-15	13: 1, 3-9, 11-15	14: 1-14
Visibility duration	14: 1-9, 11-15	13: 1, 3-9, 11-15	13: 1-9, 11-14
Coordinate SD	14 plotted indices	15 plotted indices	14 plotted indices
Elevation	24 hourly bins	24 hourly bins	24 hourly bins
2DRMS, CEP, SEP, MRSE	Rendered plot only	Rendered plot only	Rendered plot only

Figure 2. Data-acquisition chain used at the fixed station, comprising the antenna, open-sky mount, ZED-F9P receiver and logging computer.



Data Conversion and Solution Processing

Raw observations were saved in UBX format, and hourly files were merged into daily records. RTKCONV converted the files to RINEX. The observation and broadcast navigation files were processed in RTKPOST as GLONASS-only, Galileo-only and combined GLONASS-Galileo datasets. The documented single-receiver workflow used standalone single-point positioning with no base-station or correction-stream input.

Broadcast ephemerides and the broadcast ionospheric model were selected, the Saastamoinen tropospheric model and a 15° elevation mask were applied, and output coordinates were referenced to WGS 84. Carrier-phase ambiguity resolution was not used because the solution was standalone code-based positioning. Identical settings were applied to all three constellation modes.

Carrier-to-noise-density observations were aggregated to hourly means for the constellation-specific signals: GLONASS L1OF and L2OF and Galileo E1 and E5b. The ZED-F9P supports Galileo E1B/C and E5b I/Q tracking; The number of satellites contributing at each epoch produced daily minimum, maximum and mean NSV values. Satellite availability was measured from the interval between the first and last valid epoch for each tracked satellite. Tec-Suite generated elevation angles, which were grouped into hourly averages.

Position-solution Precision Measures

Daily standard deviations of latitude, longitude and ellipsoidal height were calculated from the position solutions. Angular latitude and longitude standard deviations were converted to metres using one minute of arc as 1,852 m and the mean latitude to scale longitude. Following Santra et al. (2019), the converted longitude, latitude and altitude standard deviations were denoted by sigma-x, sigma-y and sigma-z, respectively. These quantities describe repeatability around the daily mean and not error relative to an independently surveyed control coordinate.

$\sigma_{\text{lat}} = \text{SD}(\text{latitude in arcmin}) \times 1852$	(1)
$\sigma_{\text{lon}} = \cos(\phi) \times \text{SD}(\text{longitude in arcmin}) \times 1852$	(2)

The horizontal and three-dimensional containment measures were calculated as follows.

$2\text{DRMS} = 2\sqrt{(\sigma_x^2 + \sigma_y^2)}$	(3)
$\text{CEP} = 0.62\sigma_y + 0.56\sigma_x$	(4)
$\text{SEP} = 0.51(\sigma_x + \sigma_y + \sigma_z)$	(5)
$\text{MRSE} = \sqrt{(\sigma_x^2 + \sigma_y^2 + \sigma_z^2)}$	(6)

Here, 2DRMS is a high-probability horizontal containment radius, CEP is the 50% horizontal containment radius, SEP is the 50% three-dimensional containment radius and MRSE is the mean radial spherical error. In this study, all four were calculated from scatter about the daily mean. They are therefore reported as precision or repeatability measures rather than absolute accuracy measures.

Statistical Analysis

Daily NSV and coordinate standard deviations were summarised by the mean, sample standard deviation and observed range. Visibility duration was summarised by the mean, median, interquartile range and observed range. Paired Wilcoxon signed-rank tests compared GLONASS and Galileo values on the same retained observation days, with two-sided alpha=0.05. Signal statistics were calculated from the 24 monthly hourly mean points shown in Figure 3 and rounded to 0.1 dB-Hz. The primary monthly NSV summaries used all valid paired days. A sensitivity analysis was then restricted to the 12 calendar days available in all three NSV tables: days 1, 3-9 and 11-14. No significance test was applied to the 2DRMS, CEP, SEP and MRSE curves because the retained thesis provided only a rendered plot whose x-axis does not preserve a traceable dated numerical series. Those comparisons are descriptive.

RESULTS AND DISCUSSION

Signal Quality

Figure 3 presents the 24 monthly hourly mean C/N₀ values. Galileo E1 and GLONASS L1OF were similar

within each month. Their mean $\pm$ SD values were 36.8 ± 0.4 and 36.9 ± 0.6 dB-Hz in May, 36.8 ± 0.3 and 37.1 ± 0.5 dB-Hz in June, and 37.6 ± 0.5 and 37.9 ± 0.7 dB-Hz in August (Table 1). Neither constellation therefore had a consistent first-frequency advantage at this site.

The second-frequency comparison was different. Galileo E5b averaged 41.6 ± 0.2 , 42.7 ± 0.3 and 42.5 ± 0.2 dB-Hz in May, June and August, respectively. GLONASS L2OF averaged 37.6 ± 0.4 , 37.8 ± 0.5 and 37.4 ± 0.4 dB-Hz. The separation persisted across the 24 hourly means. This receiver-, antenna-, signal- and site-specific result supports stronger E5b tracking in the experiment but does not isolate transmitter power, modulation, antenna gain or propagation effects.

Figure 3. Monthly hourly mean C/N₀ for Galileo E1 and E5b and GLONASS L1OF and L2OF in (a) May, (b) June and (c) August 2025. The L1 and L2 labels embedded in the source figure correspond to E1/E5b for Galileo and L1OF/L2OF for GLONASS.

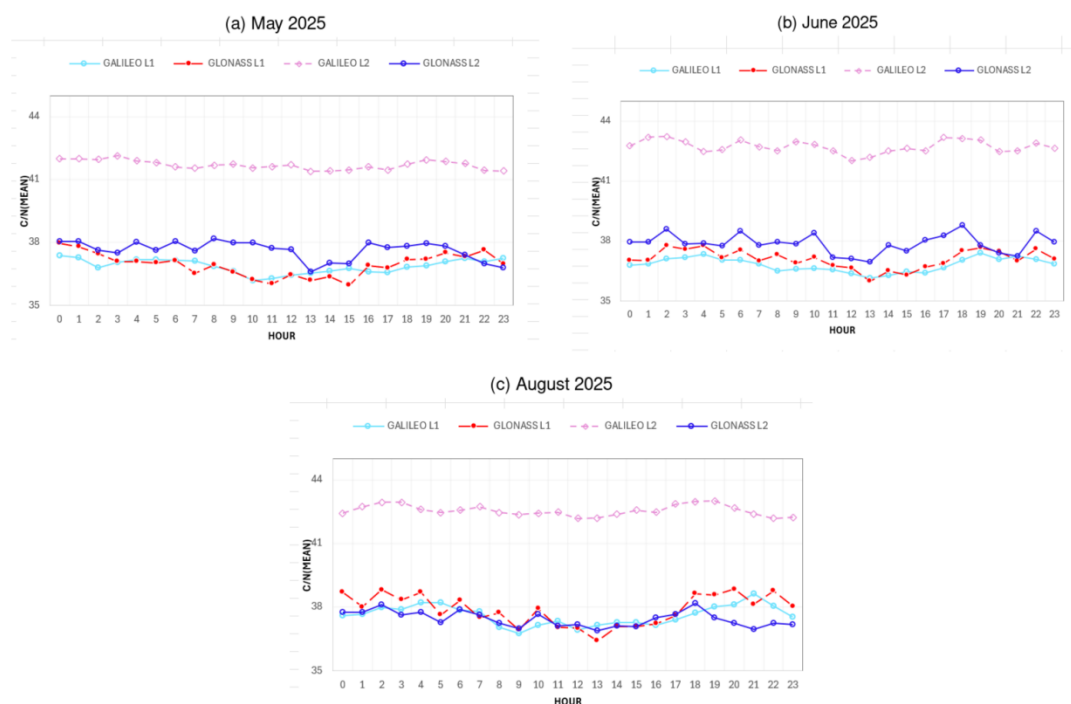


Table 1. Descriptive statistics for the 24 monthly hourly mean C/N₀ values

Month	Galileo E1	Galileo E5b	GLONASS L1OF	GLONASS L2OF
May	36.8 ± 0.4 [36.0-37.3]	41.6 ± 0.2 [41.4-42.1]	36.9 ± 0.6 [36.0-38.0]	37.6 ± 0.4 [36.6-38.1]
June	36.8 ± 0.3 [36.2-37.3]	42.7 ± 0.3 [42.0-43.1]	37.1 ± 0.5 [36.0-37.7]	37.8 ± 0.5 [36.9-38.7]
August	37.6 ± 0.5 [36.7-38.5]	42.5 ± 0.2 [42.2-43.0]	37.9 ± 0.7 [36.4-38.9]	37.4 ± 0.4 [36.8-38.1]

Values are mean $\pm$ sample SD [minimum-maximum], in dB-Hz, computed from the 24 hourly points in Figure 3.

Satellite Visibility and Availability

Both standalone modes met the four-satellite minimum throughout the retained NSV tables. Galileo had a higher daily mean NSV than GLONASS in May, June and August (Table 2), with paired Wilcoxon $p=0.00024$ in each month. The comparison was paired within month, so each constellation used the same days. Restricting the analysis to the 12 calendar days shared by all three monthly tables gave the same

ordering: GLONASS/Galileo means were 5.77/7.29 in May, 5.81/7.43 in June and 5.79/7.21 in August. The monthly conclusion was therefore unchanged by unequal day counts. The August GLONASS series remains provisional because it exactly duplicates the May values.

Table 2. Daily mean NSV descriptive statistics and paired comparisons

Month	n	GLONASS mean $\pm$ SD [range]	Galileo mean $\pm$ SD [range]	Mean difference	Wilcoxon p
May	14	5.79 $\pm$ 0.11 [5.52-5.94]	7.23 $\pm$ 0.65 [5.43-7.84]	1.44	0.00024
June	13	5.78 $\pm$ 0.13 [5.47-5.93]	7.45 $\pm$ 0.35 [6.89-8.05]	1.67	0.00024
August	14	5.79 $\pm$ 0.11 [5.52-5.94]	7.22 $\pm$ 0.65 [5.43-7.84]	1.43	0.00024*

Table 3 reports distributions rather than only extremes. The median least-tracked GLONASS duration was 6 h 49 min in May, 6 h 50 min in June and 7 h 01 min in August, compared with 2 h 19 min, 2 h 21 min and 2 h 19 min for Galileo.

For the most-tracked satellite, Galileo medians were 14 h 46 min, 15 h 25 min and 15 h 16 min, exceeding the GLONASS medians of 12 h 06 min, 11 h 00 min and 11 h 02 min. These summaries describe different satellites selected as the daily minimum or maximum and should not be interpreted as matched orbital arcs.

Table 3. Distribution of daily least- and most-tracked satellite visibility durations

Month	n	GLONASS least	Galileo least	GLONASS most	Galileo most
May	14	06:48; 06:49; 06:48-06:50 [06:41-06:55]	02:18; 02:19; 02:13-02:23 [02:11-02:26]	12:04; 12:06; 12:02-12:07 [11:57-12:08]	14:48; 14:46; 14:40-14:53 [14:36-15:05]
June	13	06:50; 06:50; 06:48-06:51 [06:46-06:54]	02:22; 02:21; 02:19-02:26 [02:10-02:34]	11:00; 11:00; 10:58-11:01 [10:56-11:03]	15:25; 15:25; 15:15-15:34 [15:03-15:48]
August	13	07:01; 07:01; 06:59-07:03 [06:56-07:04]	02:20; 02:19; 02:16-02:26 [02:12-02:30]	11:02; 11:02; 10:59-11:05 [10:54-11:09]	15:16; 15:16; 15:11-15:22 [15:03-15:26]

Each cell reports mean; median; IQR [range] in HH:MM.

Coordinate Precision

Galileo produced smaller daily coordinate standard deviations than GLONASS for latitude, longitude and altitude in every month (Figure 4 and Table 4). Paired Wilcoxon tests supported the differences for all nine month-coordinate comparisons ($p \leq 0.00012$). The largest separation was vertical: GLONASS/Galileo mean altitude SD was 23.39/8.02 m in May, 13.30/5.38 m in June and 13.36/5.31 m in August.

Horizontal scatter followed the same ordering. Mean latitude SD for GLONASS/Galileo was 9.43/3.39 m in May, 4.64/1.48 m in June and 4.11/1.46 m in August. Mean longitude SD was 9.00/3.20 m, 4.61/1.60 m and 4.64/1.71 m, respectively. The May series contained the widest ranges, especially for GLONASS altitude.

Figure 4. Daily standard deviations of latitude, longitude and altitude for GLONASS and Galileo in (a) May, (b) June and (c) August 2025.

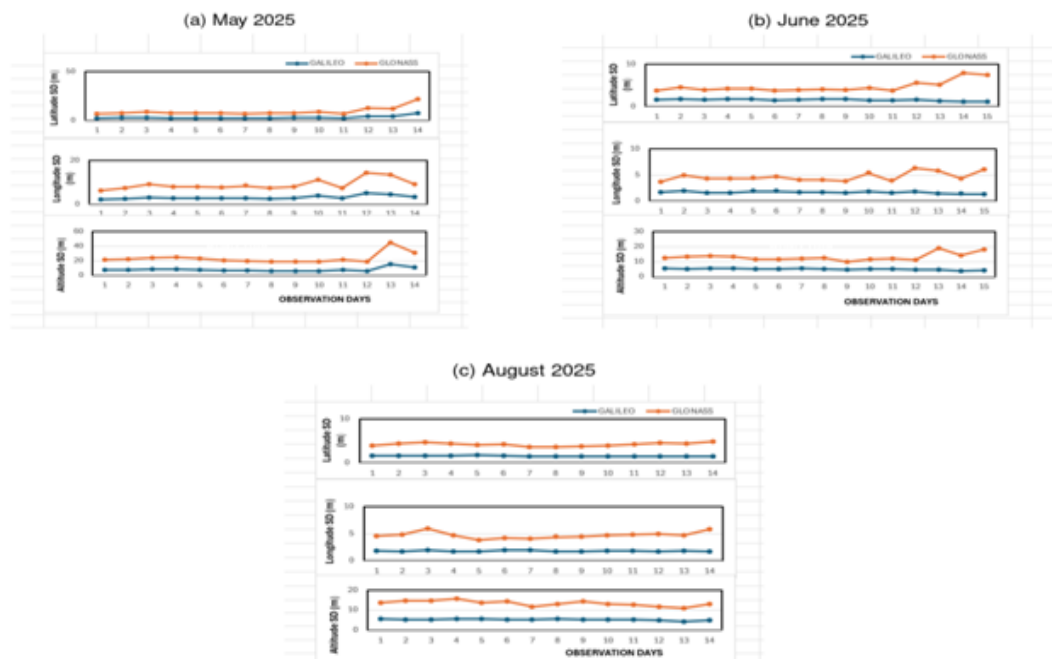


Table 4. Daily coordinate standard deviations by constellation

Month	Coordinate	GLONASS mean $\pm$ SD [range] m	Galileo mean $\pm$ SD [range] m	Wilcoxon p
May	Latitude	9.43 $\pm$ 3.99 [7.05-21.79]	3.39 $\pm$ 1.41 [2.56-7.69]	0.00012
May	Longitude	9.00 $\pm$ 2.35 [6.29-14.29]	3.20 $\pm$ 0.82 [2.29-5.14]	0.00012
May	Altitude	23.39 $\pm$ 6.70 [18.86-43.71]	8.02 $\pm$ 2.55 [6.00-15.43]	0.00012
June	Latitude	4.64 $\pm$ 1.32 [3.69-7.85]	1.48 $\pm$ 0.22 [1.08-1.69]	0.00006
June	Longitude	4.61 $\pm$ 0.84 [3.62-6.25]	1.60 $\pm$ 0.20 [1.25-1.88]	0.00006
June	Altitude	13.30 $\pm$ 2.41 [10.14-19.01]	5.38 $\pm$ 0.49 [4.23-5.92]	0.00006
August	Latitude	4.11 $\pm$ 0.38 [3.54-4.77]	1.46 $\pm$ 0.10 [1.38-1.69]	0.00012
August	Longitude	4.64 $\pm$ 0.59 [3.75-5.88]	1.71 $\pm$ 0.10 [1.62-1.88]	0.00012
August	Altitude	13.36 $\pm$ 1.33 [11.00-15.67]	5.31 $\pm$ 0.36 [4.33-5.67]	0.00012

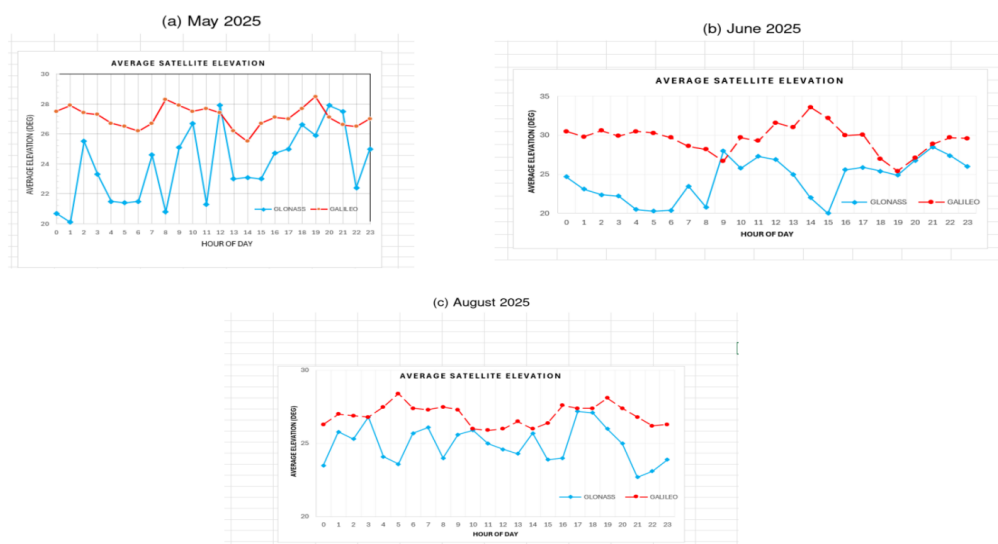
Values are mean $\pm$ sample SD [minimum-maximum]. Tests pair the plotted daily observations within each month.

Elevation-Angle Behaviour

Galileo satellites had higher and more stable hourly mean elevations during most of the observation periods (Figure 5). In May, GLONASS ranged from about 20.1° to 27.9° with a mean of 23.8°, while Galileo ranged from 25.5° to 28.5° with a mean of 27.2°. The average difference was therefore about 3.4°. In June, GLONASS ranged from about 20.0° to 28.5° and Galileo from 25.5° to 33.5°. In August, the respective ranges were 22.6-27.0° and 25.9-28.4°, with means of 24.9° and 27.0°.

Higher elevation generally shortens the atmospheric path and can reduce near-horizon obstruction and multipath. The Galileo elevation pattern is consistent with its smaller coordinate scatter, but it does not establish causation. A correlation between elevation or C/N_0 and daily coordinate SD was not calculated because the retained thesis contains elevation and C/N_0 as monthly hourly aggregates, whereas coordinate SD is retained by observation day. Correlating unmatched aggregation levels would create a spurious sample size.

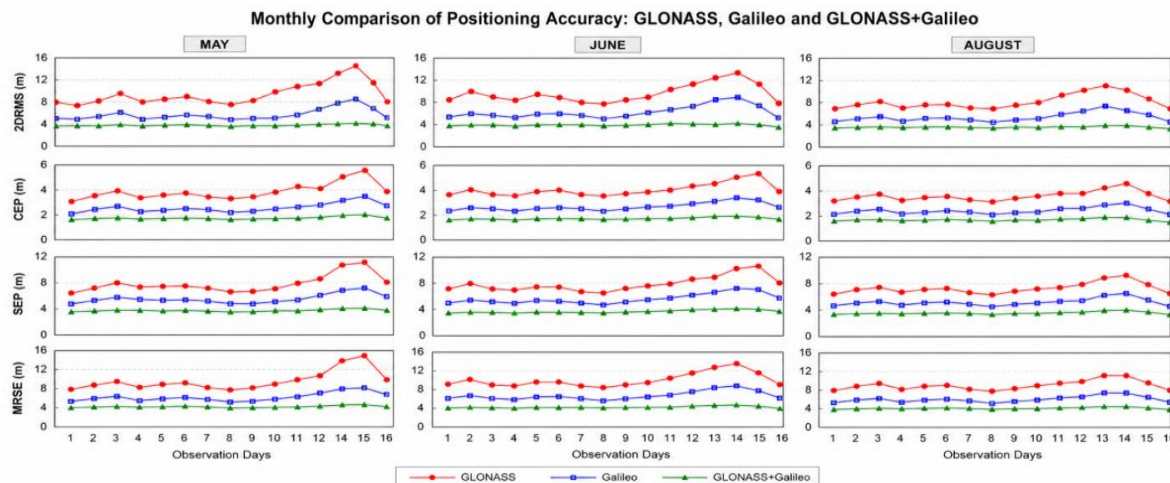
Figure 5. Hourly average elevation angles for GLONASS and Galileo in (a) May, (b) June and (c) August 2025.



Standalone and Hybrid Position-solution Precision

Figure 6 shows the descriptive ordering of the containment measures. Across the plotted series, the combined GLONASS-Galileo curve is below the Galileo-only curve, and the Galileo-only curve is below the GLONASS-only curve for 2DRMS, CEP, SEP and MRSE. Because these measures were computed from dispersion about the daily mean, lower values indicate better repeatability rather than smaller error against a surveyed truth coordinate.

Figure 6. Descriptive daily 2DRMS, CEP, SEP and MRSE precision measures for GLONASS-only, Galileo-only and combined GLONASS-Galileo solutions in May, June and August 2025. The source graphic uses the word accuracy, but the calculations quantify scatter about each daily mean.



The descriptive hybrid ordering is consistent with published evidence that additional constellations can improve observation redundancy and geometry (Chen et al., 2021; Jin et al., 2022; Mahato et al., 2023). The

standalone comparison is not between equivalent systems. GLONASS and Galileo differ in orbit geometry, active satellite population, signal structure and the specific L1OF/L2OF and E1/E5b observations tracked by this receiver. The results therefore describe these operational configurations at this site; they do not isolate a constellation effect or imply that one system is universally superior.

CONCLUSION

This study compared GLONASS-only, Galileo-only and combined GLONASS-Galileo processing at a fixed low-latitude station in Ogbomoso. Galileo E5b had higher hourly mean C/N_0 than GLONASS L2OF, and Galileo had higher daily mean NSV and lower coordinate standard deviations on the retained paired days. The NSV ordering was unchanged on the 12 calendar days shared by all three months. The combined solution had the lowest plotted 2DRMS, CEP, SEP and MRSE values, but that comparison remains descriptive because the underlying dated numerical series was not retained. The evidence supports improved repeatability from joint processing at the study site, not a general claim of absolute positioning accuracy.

LIMITATIONS AND RECOMMENDATIONS

Further work should archive raw UBX and RINEX files, RINEX headers, RTKPOST configuration files and daily numeric outputs with a processing log that records exclusions. A surveyed control coordinate should be used to separate bias from repeatability. PDOP, HDOP and VDOP, receiver tracking status, multipath indicators, total electron content and scintillation indices should be exported at matching epochs. These records would permit mixed-effects or paired day-level models linking geometry and signal quality to coordinate dispersion and would allow the hybrid result to be tested rather than assessed only from plotted curves.

DECLARATIONS

Author Contributions

All listed authors contributed to the conduct of the research and the preparation and revision of the manuscript. All authors read and approved the final version of the manuscript for submission.

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Conflict of Interest

The authors declare that they have no conflicts of interest.

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