International Journal of Maritime and Interdisciplinary Research
©2025 IJMIR/Volume 8(1) July-December | ISSN: 2734-3286.

Journal homepage: www.ijmir.edu.ng

Investigation of GPS+GALILEO Satellite Hybrid Operation towards Seamless and Improved Operation in Nigeria

Adeyemi Abiola Adeola[1], Adewumi Adebayo Segun[1], Ogobor Efua Anthony[1,2], Alagbe George Atilade[1], Adewumi Hope Kofoworola[1], Afolayan Oluwatobi Nehemiah[1]

[1]Department of Pure and Applied Physics, Ladoke Akintola University of Technology, Oyo State, Ogbomoso, Nigeria

[2]Physical and Life Science Division, National Space Research and Development Agency, Abuja, Nigeria

Abstract

In low-latitude regions, ionospheric conditions can degrade Global Navigation Satellite Systems (GNSS) accuracy, this study investigates the performance of Global Positioning System (GPS), Galileo, and combined GPS+Galileo positioning in a low-latitude environment over Ogbomoso, Nigeria, using dual-frequency u-blox ZED-F9P observations collected at 4 Hz in May 2025. A static reference station at the Ladoke Akintola University of Technology (LAUTECH) GNSS Laboratory logged raw GNSS data, which were processed to obtain carrier-to-noise density ratio (C/N_0), number of satellites visible, satellite elevation angles, positional dispersion, and Single Point Positioning (SPP). Accuracy metrics were used to evaluate the position solution. Results show that Galileo E5 provides the highest and most stable C/N_0 (≈41–42 dB-Hz), while all signals exhibit a systematic midday C/N_0 dip around 13:00–15:00 UTC, identifying a vulnerability window for critical operations. GPS offers more stable satellite visibility and consistently lower standard deviations in latitude, longitude, and altitude than Galileo, whereas Galileo maintains higher mean elevation angles. The GPS+Galileo hybrid solution delivers the best overall performance, improving SPP accuracy by approximately 8–11% relative to GPS-only and up to 50% compared with Galileo-only, depending on the metric. The findings support prioritising hybrid GPS+Galileo operation and time-aware mission planning to enhance positioning reliability in equatorial low-latitude regions.

Keywords: GPS; Galileo; GNSS; Hybrid positioning; C/N_0; SPP accuracy

***Corresponding authors:** gaalagbe@lautech.edu.ng and asadewumi@lautech.edu.ng

1.0 Introduction

In recent decades, Global Navigation Satellite Systems (GNSS) have become indispensable to modern society, enabling critical services in transportation, precision agriculture, telecommunications, disaster management, scientific research, and national infrastructure (Ogobor et al., 2025). By providing continuous, global Positioning, Navigation, and Timing (PNT), GNSS now underpins digital transformation and a wide range of technology-driven applications. While the major constellations, Global Positioning System (GPS), GLONASS, Galileo, and BeiDou can each provide standalone positioning, many modern applications increasingly rely on multi-constellation (hybrid) operation to improve satellite availability, strengthen redundancy, and enhance positioning reliability.

This need is especially pronounced in low-latitude regions such as Nigeria, where ionospheric disturbances can severely degrade GNSS signal quality and positioning performance (Oladipo et al., 2018; Adewumi et al., 2025; Ogobor et al., 2025). The West African sector lies beneath the equatorial ionization anomaly (EIA), where strong Total Electron Content (TEC) gradients and post-sunset plasma instabilities promote ionospheric scintillation, causing signal fading, cycle slips, and degraded tracking (Akala et al., 2014; Ikani et al., 2023; Oladipo et al., 2018; Vasylyev et al., 2022).

Observations over Nigeria (e.g., Lagos and Ilorin) show clear equinoctial seasonality and predominantly night time scintillation, indicating that GNSS users in the region face recurring performance stress (Akala et al., 2014; Oladipo et al., 2018). More recent GNSS-TEC/ROTI analyses across multiple Nigerian stations further confirm that irregularity occurrence remains persistent and exhibits strong seasonal and latitudinal structure (Ikani et al., 2023; Onuchukwu et al., 2024; Ogobor et al., 2025).

These ionospheric conditions translate directly into measurable navigation impacts. Across the African low-latitude sector, GPS single point positioning (SPP) errors can reach approximately 25 m horizontally and 45 m vertically, with a substantial fraction of night time errors linked to plasma irregularities, highlighting the vulnerability of single-constellation positioning under disturbed ionospheric conditions (Abe et al., 2023). Consequently, there is growing interest in hybrid GNSS operation (e.g., GPS+Galileo), which can increase the number of satellites in view, improve positioning geometry (GDOP), and provide additional measurement redundancy when signals are

intermittently degraded (Dan et al., 2021; Vankadara et al., 2023; Adewumi et al., 2025). Beyond constellation choice, recent work also emphasizes the importance of high-resolution measurements and resilient receivers for accurately quantifying ionospheric effects and assessing performance under real conditions (Adewumi et al., 2025; Ogobor et al., 2025).

At the same time, West African GNSS research has increasingly adopted affordable monitoring platforms, including low-cost dual-frequency receivers and local ionospheric monitoring approaches (Bolaji et al., 2023; Okoh et al., 2024; Adewumi et al., 2025; Ogobor et al., 2025). However, much of the existing literature in Nigeria and West Africa focuses on ionospheric characterization and instrument validation, with comparatively fewer field studies that directly compare GPS-only, Galileo-only, and combined GPS+Galileo performance using common metrics such as carrier-to-noise density ratio (C/N_0), satellite visibility/elevation characteristics, and SPP accuracy under local low-latitude conditions. Although multi-constellation benefits are widely reported globally (Li et al., 2019; Angrisano et al., 2023, Mahato et al 2023, Adewumi et al., 2025), location-specific evidence is still needed to clarify how these gains manifest under Nigeria's equatorial ionospheric dynamics.

Motivated by the limited location-specific evidence for hybrid GNSS performance in Nigeria, this study evaluates GPS-only, Galileo-only, and combined GPS+Galileo operation using dual-frequency u-blox ZED-F9P observations collected at the Ladoke Akintola University of Technology (LAUTECH) GNSS Laboratory in Ogbomoso, Nigeria. Using high-rate (4 Hz) data, we quantify C/N_0, satellite visibility and elevation characteristics, and SPP accuracy using standard positioning metrics. The next section describes the observation setup, data processing workflow, and performance indicators used to compare the three positioning modes.

2.0 Materials and Methods

A static mode real-time GNSS Reference Coordinate (RC) point was established in LAUTECH GNSS Laboratory (LGL), Ogbomoso, Nigeria depicted in Figure 1. Figure 2 shows the experimental setup of a dual-frequency u-blox ZED-F9P receiver, equipped with a multi-band patch antenna, deployed to collect continuous 4 Hz GNSS observations over a two-week period in May 2025. Raw logged UBX files were converted to Receiver Independent Exchange (RINEX) format 3.03 using Real Time Kinematic LIBRARY (RTKLIB) software, after which the dataset

was processed in four steps. First, carrier-to-noise density ratio (C/N_0) values were extracted and analysed in MATLAB to examine diurnal signal quality variations.

Second, the number of satellites visible (NSV) per epoch was obtained from RTKPOST outputs, and satellite elevation angles were evaluated using Tec-suite. Third, positional stability was assessed by computing the standard deviations of latitude, longitude, and altitude solutions. Finally, Single Point Positioning (SPP) accuracy was evaluated using established metrics, including two-Distance Root Mean Square (2DRMS), Circular Error Probable (CEP), Spherical Error Probable (SEP), and Mean Radial Spherical Error (MRSE) detailed in (Santra et al 2019).



Figure 1: Geographical Locations of the Study Area over LAUTECH, Nigeria (8°10′18″N, 4°16′18″E) (Google Earth. 2025)

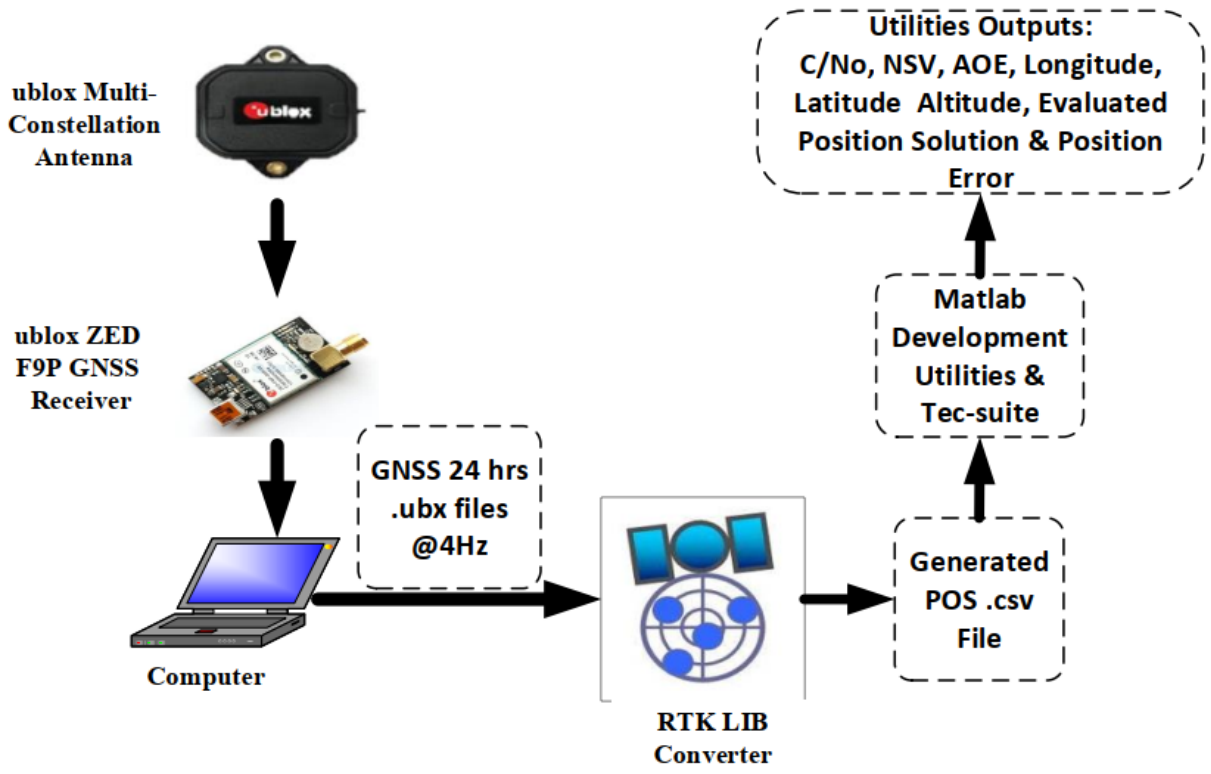


Figure 2: Experimental Setup for the GPS+Galileo Position Solution Study

3.0 Results and Discussion

Figure 2 presents the May hourly-mean C/N₀ plot curve per signal. It was observed that Galileo E5 had the highest signal strength at about 41 to 42 dB-Hz throughout the day, the GPS L1 range was within approximately 36 to 39 dB-Hz, GPS L2 was a little lower than GPS L1, and Galileo E1 was generally the lowest, just below GPS L2. Diurnal changes were small, and midday dip was observed at approximately 13:00 to 15:00 UTC, which was followed by a gentle evening recovery, and the curves remain stable, showing that the May pattern is consistent rather than day-specific.

The recurring midday dip (≈13:00–15:00 UTC) is most likely caused by a repeatable change in satellite geometry and reception conditions. When the average satellite elevation is lower, the antenna gain typically decreases and multipath effects become stronger, both of which reduce C/N₀ (Peppa and Psimoulis, 2023; Karimidoona et al., 2023). A second possible contributor is local in-band interference, which increases the noise level (N₀) and lowers C/N₀ even if the satellite signal power is unchanged (Garcia-Pena et al., 2021). Although not expected to produce a strictly daily pattern, solar radio bursts can also reduce GNSS C/N₀ on the dayside and can be checked using

space-weather records for the observation dates (Sato et al., 2019). This period should be treated as a vulnerability window; to limit performance degradation, it is advisable to apply mitigations such as combining multiple constellations and frequencies or scheduling critical operations outside these hours.

It was also observed that the E5 performed best in terms of C/N₀, which could be as a result of the Galileo satellites orbit height which is slightly higher than that of GPS satellites. Galileo E5 also shows a higher C/N₀ because its wideband AltBOC (15,10) modulation provides a sharper correlation peak, which helps the receiver track the signal more cleanly and reduces the impact of multipath compared with narrower-band signals (Padokhin et al., 2021; Tawk et al., 2012). In addition, E5 includes a pilot (data-less) component, allowing longer integration in the tracking loops and improving receiver sensitivity, which can appear as higher and more stable C/N₀ (Borio, 2023; Tawk et al., 2012). Furthermore, this result showed that both bands remain well above common tracking thresholds of approximately 36–37 dB-Hz, which implies that both constellations delivered a reliably high C/No throughout the monthly diurnal cycle.

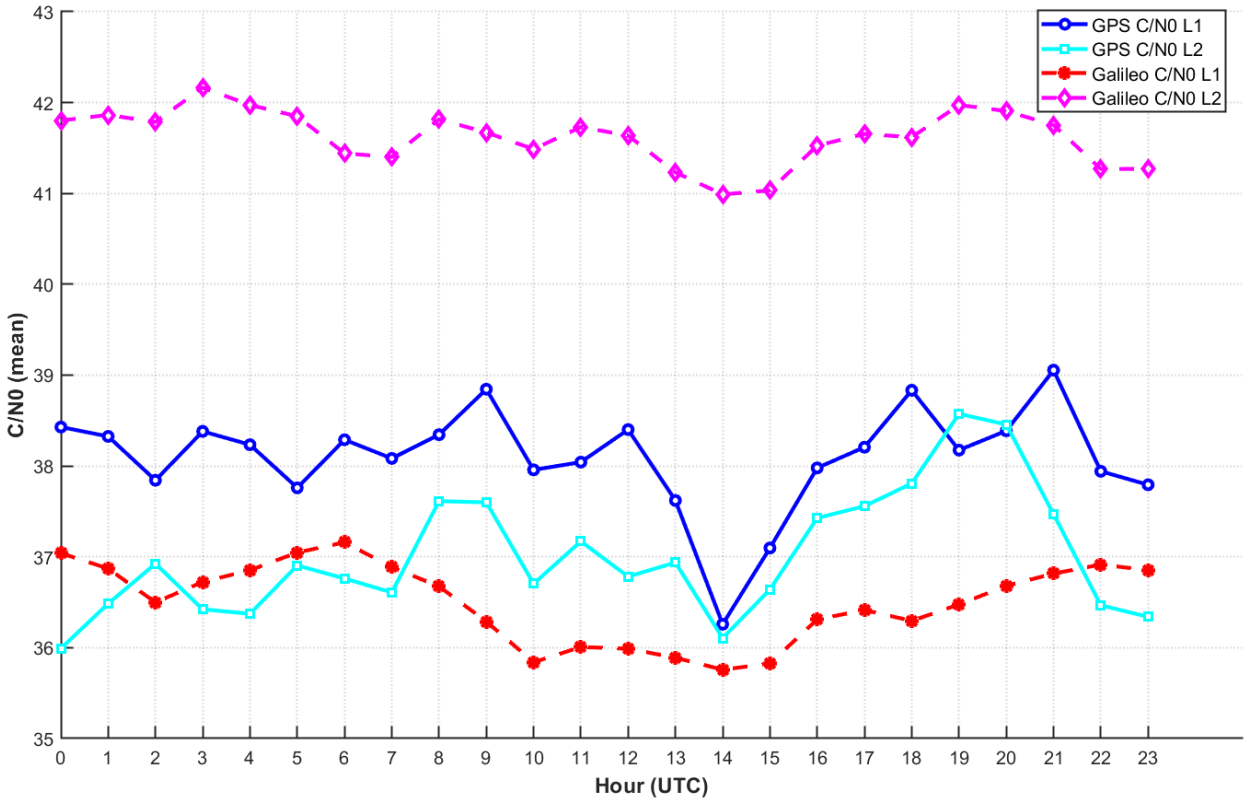


Figure 2: May Hourly Mean C/No Behavior at L1 and L2 Bands

Table 1 shows the daily NSV for both GPS and Galileo constellations during the observation period in May 2025. The table reports the minimum, maximum, and average number of satellites observed each day for the two constellations. For the GPS constellation, the results indicated a high level of stability throughout the observation period. The minimum NSV consistently remained at 6 satellites, while the maximum reached 11 on most days. The daily average was steady at approximately 8.2 satellites, with only minor fluctuations recorded. This confirmed that GPS provided reliable coverage, ensuring that users in the study region had access to a sufficient number of satellites at all times. Since a minimum of 4 satellites is required for a three-dimensional position fix, the consistent availability of 6 or more satellites demonstrated the robustness of the GPS constellation for both standard navigation and high-precision techniques such as Precise Point Positioning (PPP).

In contrast, the Galileo constellation displayed greater variability in satellite visibility. The minimum NSV was consistently 4 satellites, which is just adequate for 3D positioning, but the maximum values ranged between 8 and 11, depending on the day. The daily averages fluctuated between 5.43 satellites on 14 May and 7.84 satellites on 13 May. This variability suggested that, while Galileo provided adequate coverage, it did not match the stability demonstrated by GPS. Nevertheless, the higher average values observed on some days confirmed that Galileo was capable of delivering performance comparable to GPS under favourable orbital conditions. The comparison between the two systems revealed that GPS consistently outperformed Galileo in terms average satellite visibility.

Table 1: GPS and Galileo Constellations NSV

Observation Days	GPS			Galileo		
	NSV			NSV		
	Min	Max	Ave	Min	Max	Ave
01-05-25	6.00	11.00	8.23	4.00	11.00	7.32
02-05-25	6.00	11.00	8.23	4.00	11.00	7.28
03-05-25	6.00	11.00	8.23	4.00	10.00	7.33
04-05-25	6.00	11.00	8.23	4.00	11.00	7.58
05-05-25	6.00	11.00	8.23	4.00	9.00	6.91
06-05-25	6.00	11.00	8.23	4.00	11.00	7.77
07-05-25	6.00	11.00	8.23	4.00	11.00	7.74
08-05-25	6.00	11.00	8.24	5.00	10.00	7.09
11-05-25	6.00	11.00	8.24	4.00	11.00	7.36
12-05-25	6.00	11.00	8.23	4.00	11.00	7.32
13-05-25	6.00	11.00	8.23	4.00	11.00	7.84
14-05-25	6.00	11.00	8.23	4.00	8.00	5.43
15-05-25	6.00	10.00	8.06	4.00	9.00	6.38
16-05-25	6.00	11.00	8.23	4.00	11.00	7.73

Figure 3 presents the average angle of elevation of GPS and Galileo satellites varied over a 24-hour period for the observation period, providing insight into their relative visibility patterns. The hourly variation in average elevation showed noticeable differences between the two constellations. For GPS, the average elevation ranged from 21.35° to 29.53°, with a mean value of 25.69° across the full day. The elevation profile revealed fluctuations, with lower values during the early morning hours between 3 and 6 am UTC.

It increased and peaked at 9:00, 11:00, and 21:00, respectively. There was also a decrease in the midday, from 13:00 to 15:00, which coincided with the decrease observed in the C/No data, which implies that the reduction in angle of elevation influenced the reduction in the GPS C/No at that time window. For Galileo, the average elevation values were higher and more uniform, ranging from 25.48° to 28.45°, with a mean of 27.10°. Unlike GPS, Galileo maintained a relatively stable elevation profile, showing smaller variations across the 24-hour cycle. Galileo also experienced dips similar to that of GPS but not as intense as GPS. Also, at some points an inverse pattern was observed in Galileo when compared to the GPS curve, notably at 1:00, 19:00, and 21:00 UTC,

which will serve as an advantage when using both constellations for hybrid purposes to complement each other to improve positioning performance. The midday decrease between 13:00 and 15:00 was also observed in Galileo, although not as low as that of GPS. This result showed that Galileo satellites demonstrated greater stability, maintaining higher elevation angles with only minor fluctuations. This indicates a more uniform orbital distribution during the observation period, which could have also supported consistent signal quality in the E5 band.

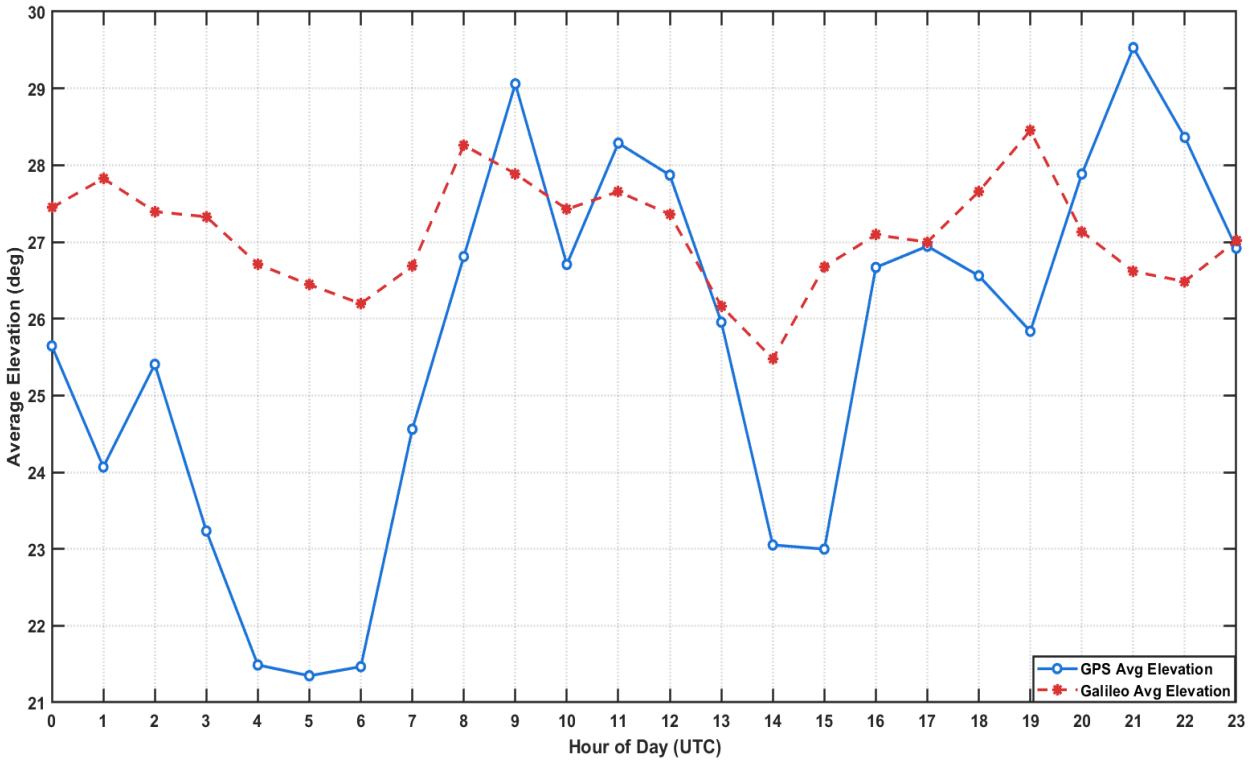


Figure 3: May Hourly Average Variation of GPS and Galileo Satellites' Average Angle of Elevation Relative to Visible Hours (1–24 h).

Figure 4 shows the daily standard deviation (SD) of latitude, longitude, and altitude gotten from the POS for GPS and Galileo during the observation period. The results revealed that GPS consistently provided lower and more stable SD error values in all three coordinate components compared to Galileo, where lower SD indicates tighter clustering and higher precision. For the

latitude component, GPS remained steady and precise, with standard deviation values ranging from 1.15 to 1.75 m and a mean of 1.54 m over the 14-day period. Galileo, on the other hand, showed higher dispersion, spanning 2.10 to 6.80 m with a mean of 2.97 m. The most notable feature was a sharp increase on Day 15, when the latitude error peaked at about 6.80 m before returning to typical values near 2 to 3 m.

The longitude component followed a similar pattern. GPS values were stable, ranging between 1.38 and 1.94 m with a mean of 1.69 m, while Galileo longitude errors varied more widely, between 1.94 and 4.51 m with a mean of 2.84 m. The largest deviation occurred on Day 13, when the Galileo longitude error rose to about 4.51 m. The altitude component displayed the largest errors for both constellations. GPS values remained comparatively stable, varying from 4.16 to 5.69 m with a mean of 5.16 m. Galileo altitude errors were consistently larger and more irregular, spanning 5.40 to 14.23 m with a mean of 7.66 m.

A significant surge was observed on Day 14, when the vertical error climbed to 14.23 m, followed by elevated values on Day 15 (about 10 m) before reaching the lowest point of 5.40 m on Day 16. Generally, the horizontal precision (latitude and longitude) was consistently tighter than the vertical precision, but in every component GPS maintained lower dispersions than Galileo. The results demonstrated a clear performance distinction between the two constellations. GPS solutions exhibited higher stability and lower standard deviations, while Galileo solutions displayed greater variability across days, particularly in the altitude component.

This variability, which surged on Day 14 and 15, coincided with days of reduced NSV as observed in the visibility results, with average NSV values of 5.43 and 6.38, respectively. It was observed when comparing the two constellations that GPS proved more precise in both horizontal and vertical components, while Galileo introduced larger scatter and day-to-day variation. However, the integration of both systems would allow users to benefit from the stable precision of GPS and the additional redundancy of Galileo, which can help reduce errors and improve geometry, especially in challenging observational environments.

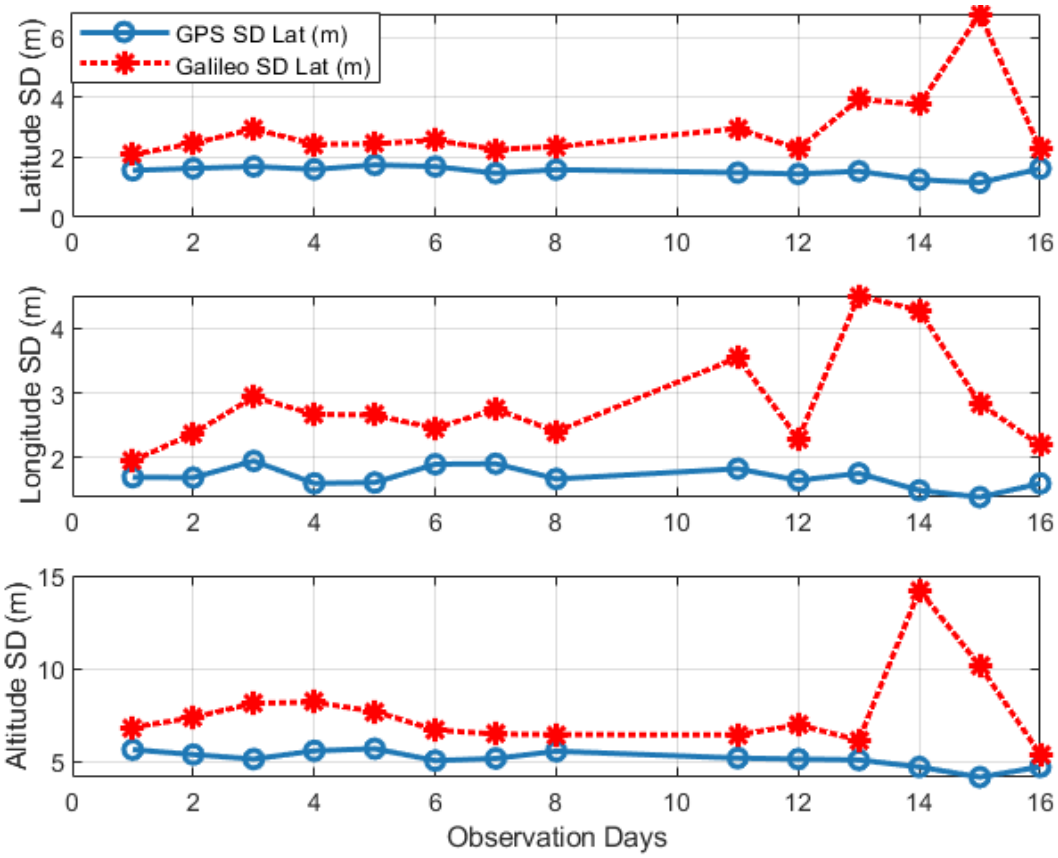


Figure 4: Standard Deviation of Latitude, Longitude, and Altitude

The performance of GPS-only, Galileo-only, and the combined GPS+Galileo hybrid positioning system was evaluated using standard accuracy metrics: 2DRMS, CEP, SEP, and MRSE, all derived from the POS solutions. These metrics offer details about horizontal precision (CEP, 2DRMS) and volumetric (SEP, MRSE) where lower values represent better accuracy. The daily variations are presented in Figure 5. The results showed a consistent hierarchy in accuracy: the hybrid solution outperformed both GPS-only and Galileo-only systems, GPS-only achieved second-best performance, while Galileo-only produced the largest errors and greatest variability. On average across all days, the GPS+Galileo hybrid achieved a 2DRMS of 4.17 m, CEP of 1.74 m, SEP of 3.85 m, and MRSE of 5.05 m. This represented an improvement of about 8 to 11% compared with GPS-only and nearly 42 to 50% compared with Galileo-only, depending on the metric.

GPS-only solutions were also precise; GPS-only achieved mean values of 2DRMS 4.57 m, CEP 1.90 m, SEP 4.28 m, and MRSE 5.65 m, remaining stable across the observation period. In contrast, Galileo-only showed higher dispersions, with average values of 2DRMS 8.32 m, CEP

3.44 m, SEP 6.87 m, and MRSE 8.77 m, and notable peaks on Days 14 and 15 when MRSE exceeded 15 m and 2DRMS rose above 14 m. The day-to-day analysis confirmed that GPS maintained steady accuracy, with its best results recorded on Day 15 (2DRMS 3.60 m and MRSE 4.54 m), while its worst performance still remained within acceptable limits, with 2DRMS reaching 5.16 m on Day 3 and MRSE reaching 6.17 m on Day 5.

Galileo, however, was far less stable, showing acceptable performance on some days but also sharp degradations on others, particularly during periods of weaker satellite availability. The hybrid solution consistently achieved the lowest errors across nearly all days and maintained stable accuracy even when Galileo-only degraded significantly. Generally, the results demonstrated that the GPS+Galileo hybrid mode delivered the most accurate and consistent position solutions. Its advantage stems from the increased number of visible satellites and improved geometric diversity, which reduce dilution of precision and smooth out constellation-specific fluctuations.

GPS-only remained reliable and precise, owing to its advanced development and strong global coverage, while Galileo-only was less consistent and more prone to errors due to its smaller constellation and limited visibility at times. Taken together, the findings show that using GPS+Galileo hybrid is the best approach for achieving reliable and high-precision position and navigation in the study area.

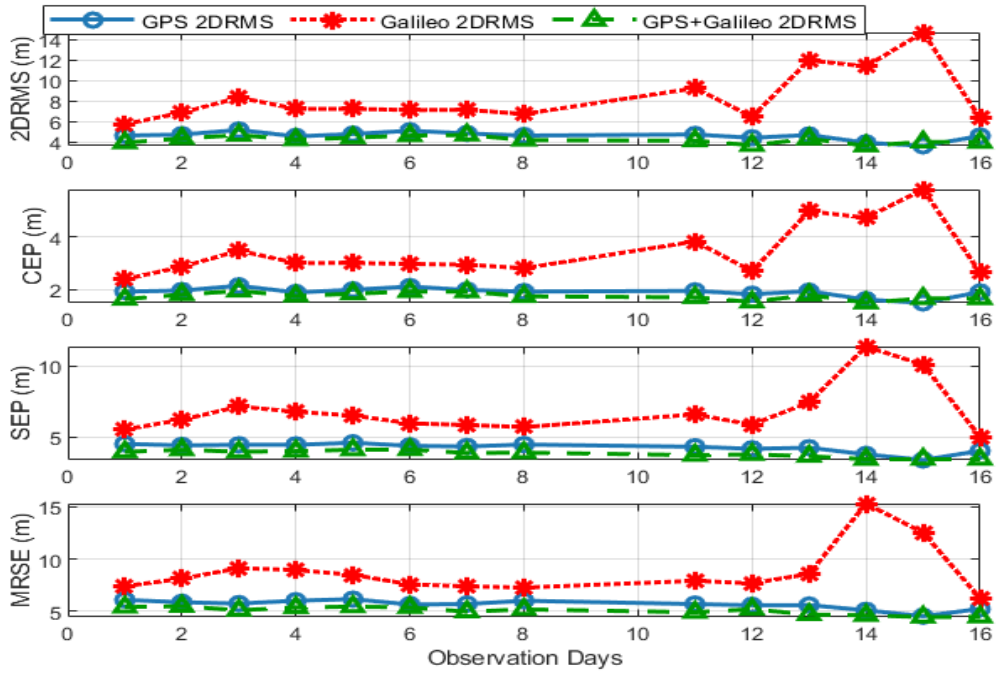


Figure 5: Position solution accuracy metrics (2DRMS, CEP, SEP, MRSE) for GPS-only, Galileo-only, and GPS+Galileo hybrid system.

4.0 Conclusion

This study compared GPS, Galileo, and GPS+Galileo hybrid performance in a low-latitude setting at LAUTECH, Ogbomoso, using May 2025 data. It examined C/N₀, NSV and satellite visibility, positional precision, elevation angles, and SPP accuracy. The GPS+Galileo hybrid solution was the best overall: it combined GPS stability with Galileo's high-elevation to achieve the lowest 2DRMS, CEP, SEP, and MRSE values, improving accuracy by about 8–11% compared to GPS-only and up to 50% compared to Galileo-only. This confirms the hybrid approach as the most effective option for reliable, high-precision positioning in the low-latitude study region.

This study advances understanding of GNSS behaviour in equatorial low-latitude regions by empirically comparing GPS and Galileo, showing GPS as more stable, Galileo as offering higher elevation and confirming that hybrid GPS+Galileo consistently delivers the best accuracy (2DRMS, CEP, SEP, MRSE). It also identifies a systematic midday C/N₀ dip around 13:00–15:00 UTC as a vulnerability window for operations. Based on these findings, the work recommends the use of high frequency data sampling rate for GNSS observations, prioritizing hybrid GPS+Galileo solutions in low-latitude regions, avoiding critical tasks during the identified midday dip, extending performance monitoring across seasons, and combining hybrid GNSS with PPP/RTK for sub-meter and centimetre-level applications such as surveying, precision agriculture, and autonomous navigation. Future research will be to investigate the impact of the midday C/N₀ dip on SPP, PPP and RTK accuracy for months and seasons.

Acknowledgment: Authors acknowledge Tertiary Education Trust Fund TETFund (TETFUND) of Nigeria for financial support through Institution Based Research Grant (TETF/IBR /UNIV/OYO STATE//2024).

References

Abe, O. E., Adeyemi, B., Ogunmodimu, O., Emmanuel, I., Oluwadare, E. J., and Oluwadare, T. S. (2023). Characterizing the accuracy of Global Positioning System for single point positioning at African low-latitude region. *Journal of Spatial Science*, 68(1), 139–154. https://doi.org/10.1080/14498596.2021.1934577

Adewumi, A. S., Dan, S., Mandal, R., and Bose, A. (2025). Effects of ionospheric delay on the position accuracy of GNSS receiver: A case study at Burdwan University, India. *Proceedings of the 8th URSI-NG Annual Conference (URSI-NG 2024)* (Vol. 12, pp. 168–174). Atlantis Press. https://doi.org/10.2991/978-94-6463-644-4_16

Adewumi, A. S., Atilade, À. G., Abiodun, A. I., Benjamin, A. G., Anthony, O. E., Oluwadara, O., and Emmanuel, E. D. (2025). PPP potential of a compact, low-cost GNSS receiver's module in a low latitude region: A case study at the LAUTECH GNSS Laboratory, Nigeria. *Proceedings of the 8th URSI-NG Annual Conference (URSI-NG 2024)* (Vol. 12, pp. 175–180). Atlantis Press. https://doi.org/10.2991/978-94-6463-644-4_17

Adewumi, A. S., Mahato, S., Samanta, S., Das, A., and Bose, A. (2025). PPP performance of dual-frequency, compact, low-cost GNSS modules: A novel study. *MAPAN*, 40(2), 421–428. https://doi.org/10.1007/s12647-025-00807-z

Akala, A. O., Amaeshi, L. L. N., Doherty, P. H., Groves, K. M., Carrano, C. S., Bridgwood, C. T., Seemala, G. K., and Somoye, E. O. (2014). Characterization of GNSS scintillations over Lagos, Nigeria during the minimum and ascending phases (2009–2011) of solar cycle 24. *Advances in Space Research*, 53(1), 37–47. https://doi.org/10.1016/j.asr.2013.09.034

Angrisano, A., Ascione, S., Cappello, G., Gioia, C., and Gaglione, S. (2023). Application of "Galileo High Accuracy Service" on single-point positioning. *Sensors*, 23(9), 4223. https://doi.org/10.3390/s23094223

Bolaji, O. S., Kaka, R. O., Scales, W. A., Fashae, J. B., Peng, Y., Rabiu, A. B., Fadiji, J. O., and Ojelade, A. (2023). TEC and ROTI measurements from a new GPS receiver at BOWEN University, Nigeria. *Atmosphere*, 14(4), 636. https://doi.org/10.3390/atmos14040636

Borio, D. (2023). GNSS data/pilot combining with extended integrations for carrier tracking. *Sensors*, 23(8), 3932. https://doi.org/10.3390/s23083932

Dan, S., Santra, A., Mahato, S., Koley, C., Banerjee, P., and Bose, A. (2021). On use of low-cost, compact GNSS receiver modules for ionosphere monitoring. *Radio Science, 56*(12), e2021RS007344. https://doi.org/10.1029/2021RS007344

Garcia-Pena, A., Julien, O., Macabiau, C., Mabilleau, M., and Durel, P. (2021). GNSS C/N0 degradation model in presence of continuous wave and pulsed interference. NAVIGATION: *Journal of the Institute of Navigation*, 68(1), 75–91. https://doi.org/10.1002/navi.405

Ikani, O., Okeke, F. N., Okpala, K. C., Okoh, D., and Rabiu, B. (2023). Diurnal and seasonal variations of the occurrence of ionospheric irregularities over Nigeria from GNSS data. *Frontiers in Astronomy and Space Sciences, 10,* 1125950. https://doi.org/10.3389/fspas.2023.1125950

Karimidoona, M., Groves, P. D., Gopaul, N., and Ramm, K. (2023). Predicting C/N0 as a key parameter for network RTK integrity prediction in urban environments. *Remote Sensing*, 15(19), 4850. https://doi.org/10.3390/rs15194850

Li, P., Zhang, X., Li, X., Li, X., Lu, C., Liu, J., and Wang, Q. (2019). Satellite availability and point positioning accuracy evaluation on a global scale for integration of GPS, GLONASS, BeiDou and Galileo. *Advances in Space Research*, 63(9), 2696–2710. https://doi.org/10.1016/j.asr.2017.07.029

Mahato, S., Sarkar, S., Goswami, M., Kundu, S., and Bose, A. (2023). GLONASS-NavIC hybrid operation from India towards seamless and improved performance. *National Academy Science Letters*, 46(3), 245–250. https://doi.org/10.1007/s40009-023-01232-z

Ogobor, E. A., Adewumi, A. S., Ayantunji, G. B., and Ogobor, E. A. (2025). Global Navigation Satellite Systems: A key player in technological advancement. *NIPES Journal of Science and Technology Research*, *7*(1), 1847–1856. https://doi.org/10.37933/nipes/7.4.2025.SI214

Ogobor, E. A., Adewumi, A. S., Ayantunji, G. B., Haruna, M. S., Azeez, I. A., and Ogobor, E. A. (2025). Seasonal variability of ionospheric scintillation over Lautech, Ogbomoso, Nigeria. *International Journal of Maritime and Interdisciplinary Research, 8(1)*, 249–263. https://www.ijmir.edu.ng

Ogobor, E. A., Adewumi, A. S., Ayantunji, G. B., Haruna, M. S., Oyelowo, O., and Ogobor, E. A. (2025). Impact of ionospheric delay on GNSS in a low-latitude region. *Research Square.* https://doi.org/10.21203/rs.3.rs-7890225/v1

Okoh, D., Obafaye, A., Dare-Idowu, O., Rabiu, B., Kashcheyev, A., Cesaroni, C., Habarulema, J. B., and Nava, B. (2024). Assessment of the performance of the TOPGNSS and ANN-MB antennas for ionospheric measurements using low-cost u-blox GNSS receivers. *Geodesy and Geodynamics*, 15(3), 291–301. https://doi.org/10.1016/j.geog.2023.11.002

Oladipo, O. A., Adeniyi, J. O., Doherty, P. H., Radicella, S. M., Adimula, I. A., and Olawepo, A. O. (2018). Ionospheric scintillation activity over Ilorin, Nigeria. *Space Weather, 16(2)*, 138–146. https://doi.org/10.1002/2017SW001728

Onuchukwu, C. C., Ottih, I. E., Leghara, E., and Okonkwo, C. P. (2024). Investigation of ionospheric irregularities over Nigeria using the Global Navigation Satellite System II. *Journal of Systematic and Modern Science Research, 4(9)*. https://berkeleypublications.com/bjsmsr/article/view/199

Padokhin, A. M., Mylnikova, A. A., Yasyukevich, Y. V., Morozov, Y. V., Kurbatov, G. A., and Vesnin, A. M. (2021). Galileo E5 AltBOC signals: Application for single-frequency total

electron content estimations. *Remote Sensing*, 13(19), 3973. https://doi.org/10.3390/rs13193973

Peppa, I., and Psimoulis, P. A. (2023). Detection of GNSS antenna oscillatory motion and multipath conditions via exploitation of multipath-induced SNR variations. *GPS Solutions*, 27, 117. https://doi.org/10.1007/s10291-023-01432-6

Santra, A., Mahato, S., Dan, S., and Bose, A. (2019). Precision of satellite based navigation position solution: a review using NavIC data. *Journal of information and optimization sciences,* 40(8), 1683-1691.

Sato, H., Jakowski, N., Berdermann, J., and Karel, J. (2019). Solar radio burst events on 6 September 2017 and its impact on GNSS signal frequencies. *Space Weather*, 17(6), 816–826. https://doi.org/10.1029/2019SW002198

Tawk, Y., Botteron, C., Jovanovic, A., and Farine, P.-A. (2012). The characteristics of tracking loops for the Galileo E5 signal. *GPS Solutions*, 16, 243–258. https://doi.org/10.1007/s10291-011-0226-8

Vasylyev, D., Béniguel, Y., Volker, W., Kriegel, M., and Berdermann, J. (2022). Modeling of ionospheric scintillation. *Journal of Space Weather and Space Climate, 12*, 22. https://doi.org/10.1051/swsc/2022016

Vankadara, R. K., Jamjareegulgarn, P., Seemala, G. K., Siddiqui, M. I. H., and Panda, S. K. (2023). Trailing equatorial plasma bubble occurrences at a low-latitude location through multi-GNSS slant TEC depletions during the strong geomagnetic storms in the ascending phase of the 25th solar cycle. *Remote Sensing, 15*(20), 4944. https://doi.org/10.3390/rs15204944