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# Seasonal Variability of Ionospheric Scintillation over Lautech, Ogbomoso, Nigeria.

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## Abstract

*This study investigates the seasonal and diurnal variability of ionospheric scintillation over Ladoke Akintola University of Technology (Lautech), Ogbomoso, Nigeria (8.17054400°N, 4.26892783°E, 403.411 m), located within the low-latitude region of the Equatorial Ionization Anomaly (EIA). The analysis was based on high-rate (4 Hz) dual-frequency Global Positioning System (GPS) data recorded at the Lautech GNSS Laboratory (LGL) between 2024 and 2025, corresponding to the peak phase of Solar Cycle 25. Amplitude scintillation indices (S4) were derived from C/N₀ observations of GPS L1 signals using a customized MATLAB framework and Tec-suite software. Data were grouped into dry and rainy seasons to evaluate the spatial distribution, elevation dependence, and temporal occurrence of moderate (S4 ≥ 0.4) and strong (S4 ≥ 0.6) scintillation events. Results indicate that scintillation occurrence is strongly influenced by season, local time, and satellite elevation. The equinox months and their surrounding months experienced the highest activity. Rainy-season months showed more intense and frequent scintillation than dry-season months. A rare and significant finding was the detection of strong midday scintillation on August 2 and 3, 2024, outside the typical post-sunset hours. These events happened at the same time as the accuracy of Precise Point Positioning (PPP) dropped, reaching 5 × 11 × 34 mm and 4 × 8 × 31 mm in latitude, longitude, and altitude, respectively. The study confirms that Nigeria's equatorial region is among the most scintillation-active globally and that amplitude fluctuations directly influence Global Navigation Satellite Systems (GNSS) positioning performance. It provides the first documented evidence of concentrated strong midday scintillation in the Nigerian sector, establishes a quantitative link between S4 intensity and PPP accuracy, and delivers a locally validated GPS 4 Hz logged dataset in Nigeria, West Africa. These results offer valuable support for GNSS performance assessments, ionospheric modeling, and the development of regional mitigation strategies for low-latitude positioning applications.*

**Keywords:** Ionospheric scintillation; Amplitude scintillation (S4) index; Global Navigation Satellite System (GNSS); Equatorial Ionization Anomaly (EIA); Precise Point Positioning (PPP)

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## 1.0 Introduction

Ionospheric scintillation, a rapid fluctuation in the amplitude and phase of trans-ionospheric radio signals caused by plasma-density irregularities, remains one of the principal error sources affecting Global Navigation Satellite Systems (GNSS) in equatorial and low-latitude regions (Dan et al., 2021; John, 2021; Adewumi et al., 2025). Around the magnetic equator, post-sunset electrodynamic processes such as the pre-reversal enhancement (PRE) of the eastward electric field and the consequent uplift of the F-region generate equatorial plasma bubbles (EPBs) and nested irregularities spanning from hundreds of kilometres to sub-meter scales (Vankadara et al., 2023).

These irregularities scatter and refract L-band signals, leading to rapid variations in carrier-to-noise ratio ($C/N_0$), cycle slips, loss of lock, and positioning errors in both code and carrier-based navigation (Oladipo et al., 2018; Vasylyev et al., 2022; Darya et al., 2024; Adewumi et al., 2025). Nigeria lies within the northern crest of the Equatorial Ionization Anomaly (EIA), a region highly prone to scintillation and ionospheric delay effects. Several African-sector studies have reported strong seasonal and diurnal dependence of scintillation, with peak activity at the equinoxes (March and September) and minimal occurrences during solstice months (June and December) (Oladipo et al., 2018; Ikani et al., 2023; Onuchukwu and Okonkwo, 2024).

For instance, long-term observations at Ilorin, Nigeria, revealed that amplitude scintillation (S4) peaked between 21:00 and 04:00 LT, particularly during equinoctial months when post-sunset electrodynamics favor EPB growth (Oladipo et al., 2018). Comparative regional studies in India and the Arabian Peninsula also show that S4 values and ROTI (Rate of TEC Index) exhibit similar equinoctial enhancements linked to solar and geomagnetic activity (Darya et al., 2024; Vankadara et al., 2023). Although previous studies have highlighted the general behavior of low-latitude ionospheric irregularities, continuous dual-frequency GNSS measurements across Nigeria remain limited due to frequent power interruptions, equipment constraints, and the conventional reliance on 1 Hz sampling rates.

The lower temporal resolution of such datasets restricts the ability to detect rapid signal fluctuations associated with small-scale plasma irregularities. This study, therefore, leverages the

availability of high-rate (4 Hz) dual-frequency GPS data to characterize S4 under real-time low-latitude conditions from the Lautech GNSS Laboratory (LGL) at Ogbomoso (8.17054400°N, 4.26892783°E, and 403.411 m) to provide a more detailed characterization of ionospheric scintillation dynamics over Ogbomoso, Nigeria. The present study leverages this capability to investigate the seasonal variability of ionospheric scintillation over Ogbomoso using standardized S4 analysis procedures and seasonal classification into Dry (November–March) and Rainy (April–October) periods.

Beyond quantifying occurrence rates, the study examines diurnal morphology, elevation-angle dependence, and the relative distribution of moderate ($S4 \geq 0.4$) and strong ($S4 \geq 0.6$) scintillation events. The resulting climatology provides a locally validated reference for GNSS users, emphasizing performance constraints on positioning applications in the Nigerian equatorial region. This paper is structured as follows: Section 2 describes the data sources and processing methodology adopted for the S4 estimation. Section 3 presents and discusses the seasonal and diurnal scintillation results in relation to atmospheric conditions. Section 4 summarizes the main conclusions and practical implications for GNSS operations in low-latitude West Africa.

## 2.0 Materials and Methods

This ionospheric scintillation and its seasonal variations across both dry and rainy seasons were achieved using static mode real-time GPS data logged using a u-blox ZED-F9P dual-frequency GNSS module together with a u-blox multiband GNSS patch antenna, as shown in Figure 1. As reported by Adewumi et al., (2025) in his published article, this receiver–antenna setup performs reliably for Precise Point Positioning (PPP) in low-latitude environments. In this setup, the antenna was placed on the top of a pole in an open sky setting at an ellipsoidal height of about 403 meters above sea level. The receiver was configured to sample data at a rate of 4 Hz, which enabled effective detection of high-frequency satellite signal fluctuations caused by ionospheric irregularities.

The data used was from 2024 and 2025, a period corresponding to the peak phase of Solar Cycle 25. Data were collected over 24-hour periods for fourteen randomly selected days in each month, spanning a total period of 12 months. The data was converted to Receiver Independent Exchange (RINEX) format 3.03 using RTKLIB software and processed with the Canadian Spatial Reference

System-PPP (CSRS-PPP) to obtain PPP final results. The converted RINEX files consisted of pseudorange, carrier phase, Doppler shift, and signal strength measurements, which were used to compute the ionospheric scintillation.

These were processed using a customized MATLAB framework capable of handling RINEX version 3.03 created by Dan et al., (2021), alongside the Tec-suite software for extracting satellite elevation and azimuth angles. All available PRNs for each day were analyzed, typically ranging between 31 and 32 satellites. To minimize low-elevation multipath and tropospheric effects, an elevation mask of 20° was applied, and only satellite observations above this threshold were retained for further processing. The S4 indices are used to categorize the severity of scintillation into weak ($0.2 < S_4 < 0.4$), moderate ($0.4 < S_4 < 0.6$), and strong ($S_4 \geq 0.6$) (Oladapo et al., 2018). Broadcast ephemeris files were used to compute satellite positions and their corresponding elevation and azimuth angles.

All data processing was performed in MATLAB using purpose-built scripts. The RINEX parser read and interpreted the file headers and bodies to extract epoch-wise observations for each satellite. The specific observation type analyzed was C1C (carrier-to-noise density ratio) on the L1 (1575.42 MHz) frequency due to its higher frequency. C/No values were extracted at the 4 Hz sampling rate to generate continuous time series. Outliers at the beginning of some data were also removed manually, the extracted C/No values were used to compute the S4 index, which quantifies fluctuations in signal amplitude induced by ionospheric irregularities. A 60-second sliding window (corresponding to 240 samples) was applied to the intensity time series, and the S4 index was subsequently calculated using the formula defined in Equation 1 (Fremouw et al., 1978; Kothawale et al., 2024).

$$\mathbf{S_4} = \sqrt{\frac{\langle \mathbf{I^2} \rangle - \langle \mathbf{I} \rangle^2}{\langle \mathbf{I} \rangle^2}} \qquad 1$$

where $I = 10^{(C/No/10)}$ denotes the signal intensity

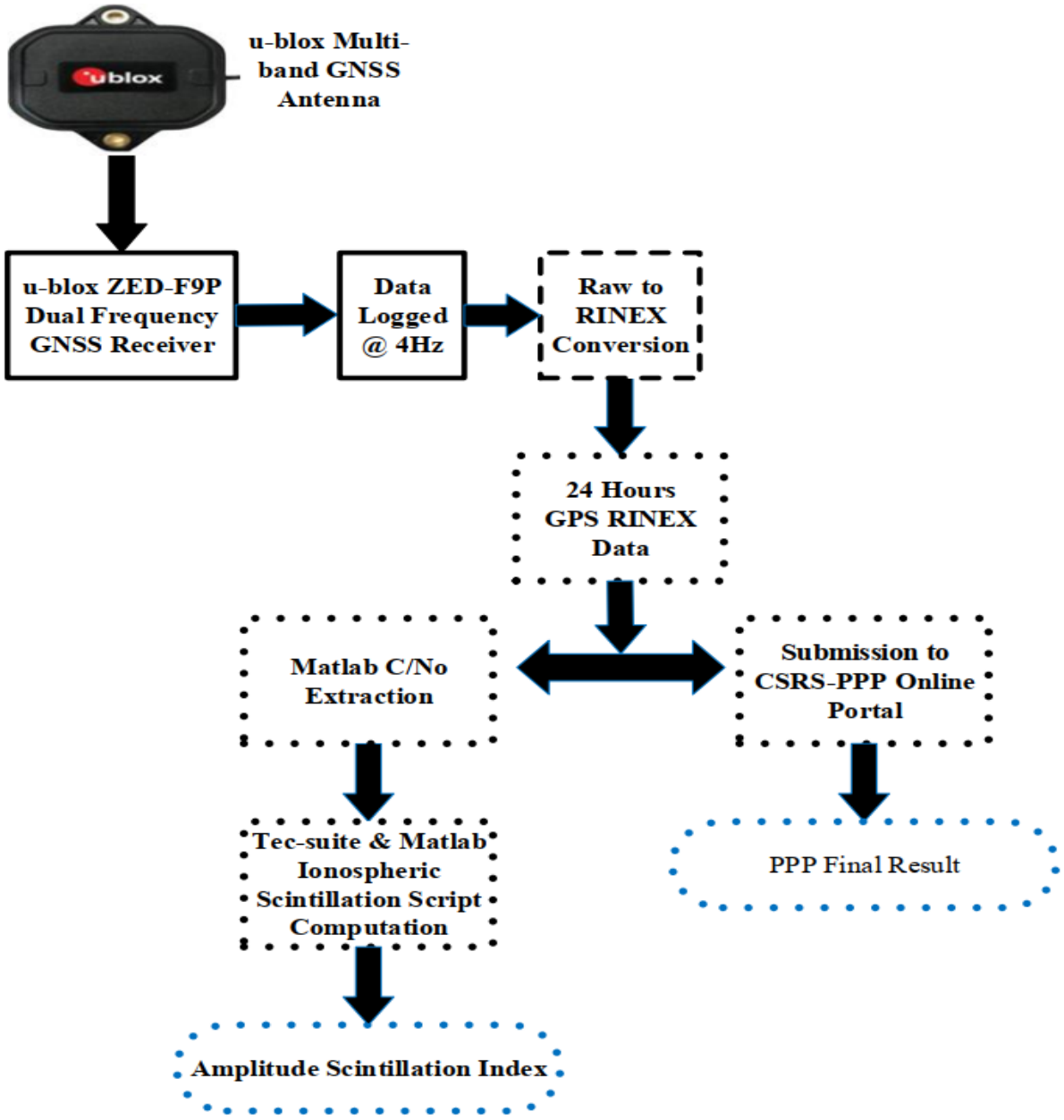



**Figure 1. Experimental setup for studying PPP performance and ionospheric scintillation at LGL, Ogbomoso, Nigeria.**

## 3.0 Results and Discussion

### 3.1 S4 and Satellite Elevation Angle Effect

Figure 2 shows the scintillation occurrence in relation to satellite elevation using April 5, 2025, data as reference. In this representation, the radial distance corresponds to the satellite's elevation angle (with the center representing zenith and the outer ring corresponding to a 30° elevation mask), while the angular position indicates the azimuth direction of the signal. Moderate scintillation events ($0.4 \leq S4 < 0.6$) and strong scintillation events ($S4 \geq 0.6$) were color-coded according to their intensity, allowing for a direct visualization of their spatial distribution. A detailed examination of the plot shows that scintillation is far from uniformly distributed across the sky.

The result shows that the majority of events cluster at low-to-mid elevation angles, particularly between 20° and 50°, where the satellite signals travel through longer, slanted paths in the ionosphere. The clusters were mostly concentrated in the southeast sector, around 120° to 170°, and in the south to south-southwest direction, between 170° and 210°. These formed arc-like tracks that reflected sustained periods of moderate scintillation along certain satellite paths. Additional clusters appear in the northwest (~300°–335°) at low and mid-elevations, though here the events are comparatively weaker.

One of the most striking features of this distribution is the presence of an isolated strong scintillation event in the west–southwest direction (~255°–265°), where the S4 index reached values close to 1. This highlights that very intense amplitude fluctuations can occur in highly localized azimuth–elevation sectors, even when the surrounding sky remains relatively calm. Its occurrence at very low elevation further suggests that signals traveling at low angles are more likely to pass through pronounced plasma gradients, increasing the likelihood of strong signal fading.

In contrast, satellites at high elevation angles (above ~70°) recorded relatively few scintillation events, and these were generally of moderate intensity. This behavior reflects the shorter vertical path length of near-zenith signals through the ionosphere, which reduces the probability of encountering irregular plasma structures. Nonetheless, the presence of some moderate scintillation

at mid-to-high elevations in the southeast quadrant (~150°–180°) indicates that ionospheric irregularities can also extend to sufficiently high altitudes to disturb near-vertical and vertical ray paths. Generally, the pattern showed that scintillation was not randomly distributed but instead exhibited clear dependencies on satellite elevation and azimuth.

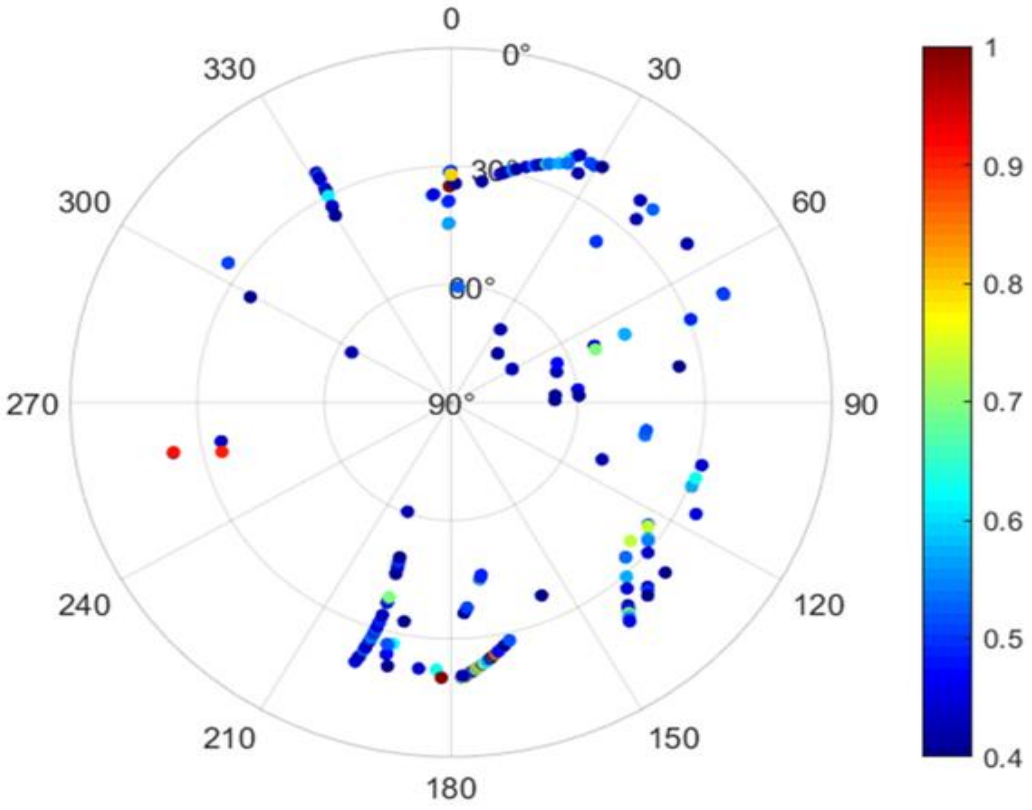



**Figure 2: S4 Index Polar Plot (Moderate and Strong Only) on April 5, 2025.**

### 3.2 Seasonal Variability of Ionospheric Scintillation in a Low-Latitude Region

Figures 3 and 4 present bar-chart plots showing the distribution of moderate and strong S4 events at low latitude during the dry and rainy seasons, respectively, using a 20° elevation cut-off. The seasonal analysis of ionospheric scintillation over Lautech, Nigeria, located within the low-latitude zone and during the peak phase of Solar Cycle 25, revealed clear differences in the intensity and occurrence of moderate and strong S4 events between the two seasons. Figure 3 shows that

scintillation activity was generally lower in the dry season compared to the rainy season (Figure 4). Across all months, moderate scintillation was the most frequent, while strong scintillation occurred less often.

In November and December 2024, moderate events numbered 2,996 and 1,202, while strong events numbered 1,007 and 211, respectively, reflecting relatively subdued activity dominated by the moderate category. A gradual increase was noted in January and February 2025, with moderate counts of 1,732 and 2,036 and strong counts of 416 and 600, respectively, consistent with conditions approaching the equinox. The highest activity occurred in March 2025, with 4,272 moderate and 1,661 strong scintillation events, which can be attributed to enhanced equinoctial effects.

Figure 4, which represents the rainy season, depicted a contrasting result, with scintillation activity being both more frequent and more intense. The absolute maximum occurred in April 2025, shortly after the March equinox, with 5,935 moderate and 2,430 strong events. This period marked the most disturbed state of the ionosphere, characterized by extended evening scintillation events, most likely driven by large-scale plasma bubbles developing under strong pre-reversal enhancement conditions. This intense post-equinox activity highlights the strong influence of ionospheric instabilities triggered during this period. After April 2025, scintillation activity showed a steady decline. During the mid-rainy season months of May, June, and July 2024, moderate events were 2,672, 2,100, and 1,650, while strong events were 980, 625, and 541, respectively.

This reduction is linked to weaker vertical drifts and altered neutral wind conditions, which limits plasma bubble development. A notable resurgence was observed in August 2024, with 3,777 moderate and 2,014 strong scintillation events. In August 2024, strong scintillation events accounted for about 35% of the total (moderate and strong), indicating very severe ionospheric irregularities that month. This highlights that scintillation risk depends not only on frequency but also on the distribution of intensity. The second equinoctial maximum was recorded in September 2024, with 4,770 moderate and 1,505 strong events. By October 2024, scintillation activity had declined to 3,204 moderate and 890 strong events, marking the transition into the dry seasonal period.

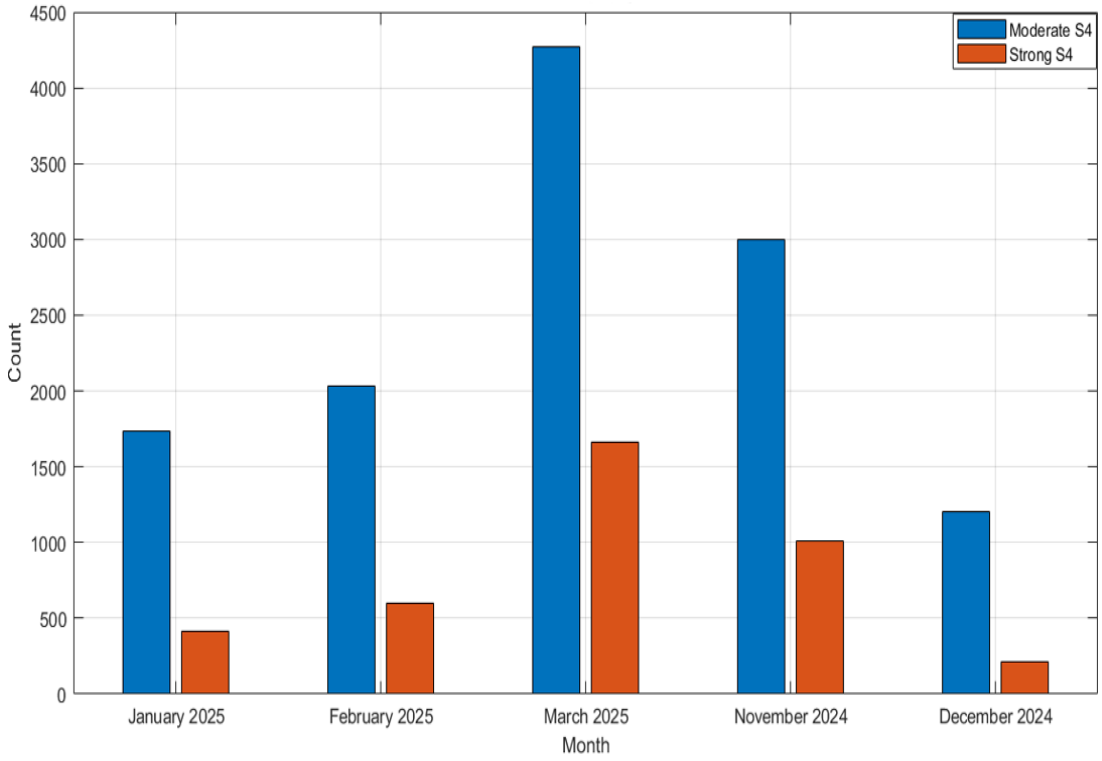



**Figure 3: Dry Season S4 over Lautech, Ogbomoso, Nigeria.**

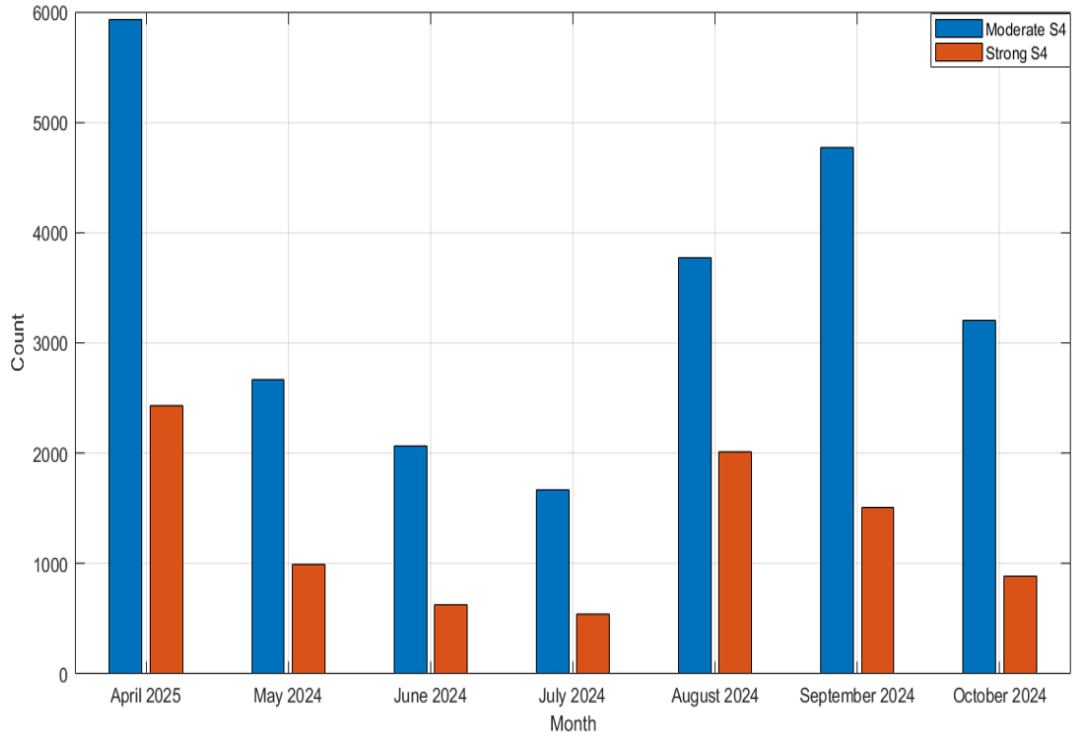



**Figure 4: Rainy Season S4 over Lautech Nigeria.**

Figures 5 and 6 present scatter plots of the diurnal variation of the S4 index for selected months in both the dry and rainy seasons (January 2025, August 2024), providing a clearer view of daily scintillation patterns. The results show that strong scintillation concentration occurrence was most pronounced during the post-sunset hours (20:00–00:00 LT) across all months. In contrast, strong scintillation occurrence concentrations before sunrise were minimal, while midday activity was largely absent throughout the campaign except in August 2024, when rare but intense strong scintillation events were recorded during both midday and evening hours, notably on August 2 and 3.

Although uncommon, these midday episodes, which have also been reported by Kothawale et al., (2024), represented some of the most severe scintillation events observed and coincided with localized increases in PPP uncertainty. During these two days, positioning accuracies degraded significantly, reaching values of 5 × 11 × 34 mm and 4 × 8 × 31 mm in latitude, longitude, and altitude, respectively, thereby accounting for the worst two observation days in August. The appearance of these midday events during the rising phase of Solar Cycle 25 may be linked to increased solar radiation, enhanced background electron density, or gravity-wave disturbances that helped create localized ionospheric irregularities even without the normal evening uplift.

These rare events highlight that the equatorial ionosphere can sometimes produce strong irregularities outside the usual post-sunset period. The relationship between strong scintillation and degraded PPP accuracy clearly shows how ionospheric irregularities affect GNSS performance. During strong scintillation, signal fading and rapid phase changes increase the risk of cycle slips and loss of lock, resulting in reduced positioning accuracy. Even though dual-frequency receivers help correct ionospheric delay, severe scintillation still causes short-term instability in the navigation solution.

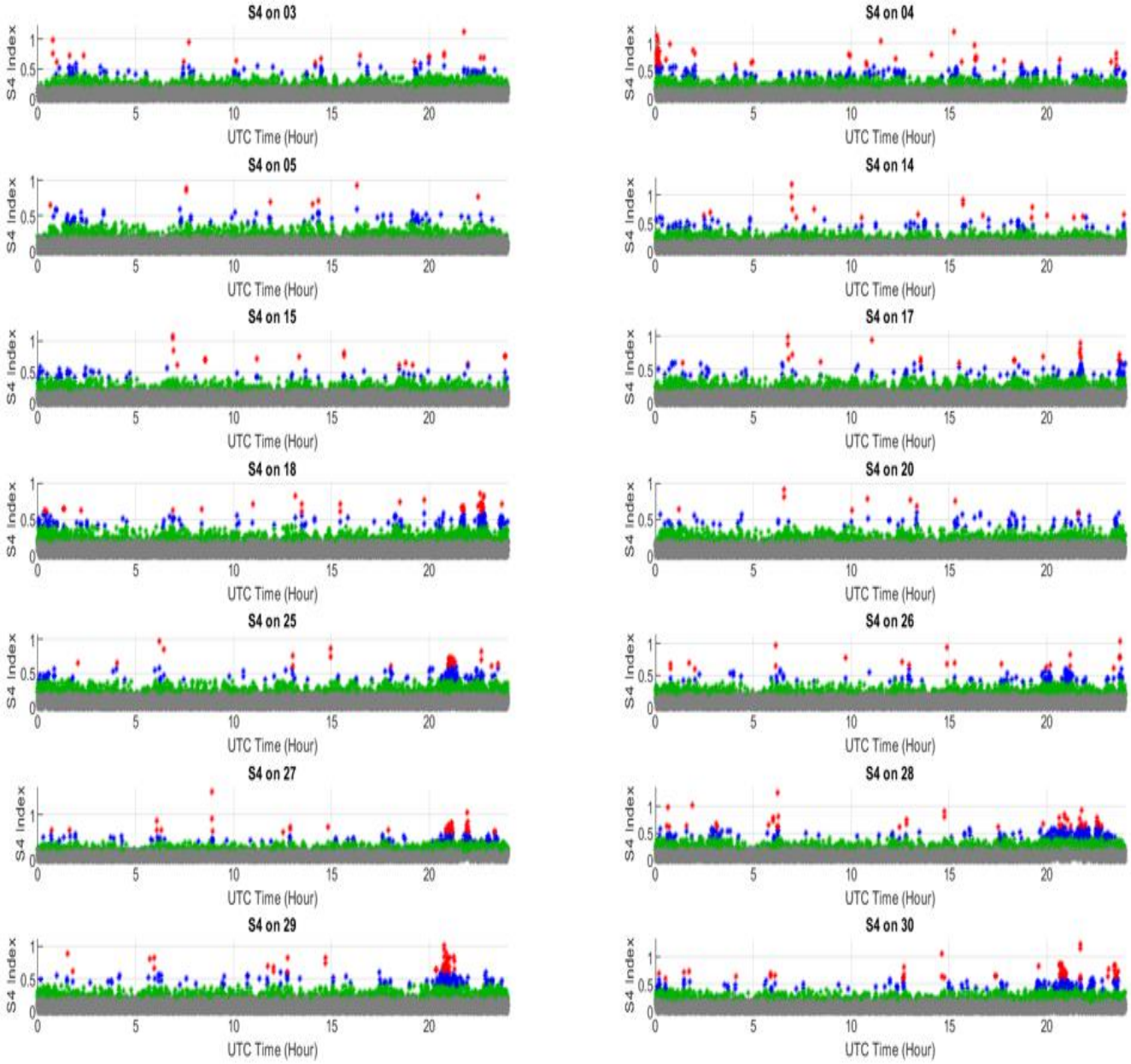



**Figure 5: January 2025 S4 Index Scatter Plots**

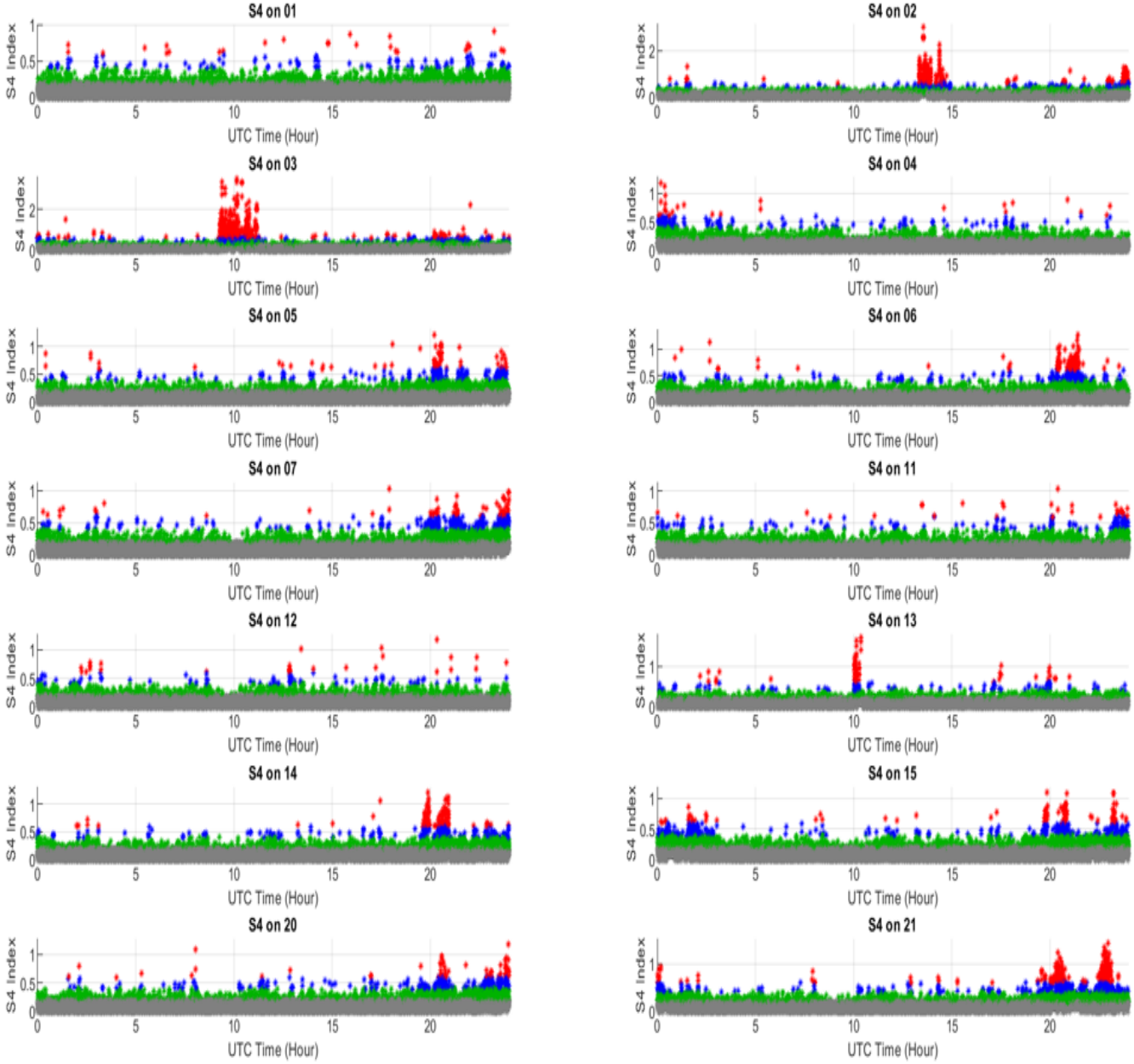



**Figure 6: August 2024 S4 Index Scatter Plots**

## 4.0 Conclusion

This study investigated the seasonal, diurnal, and spatial variability of ionospheric scintillation over Ogbomoso, Nigeria, using high-rate (4 Hz) dual-frequency GPS observations recorded at the LGL during the peak phase of Solar Cycle 25. The results clearly show that scintillation occurrence in this equatorial region varies strongly with both season and local time, confirming that Nigeria lies within one of the most scintillation-prone zones of the EIA. Scintillation activity was highest during the equinox months, with April 2025 showing the overall maximum intensity. The rainy season recorded more frequent and stronger scintillation compared to the dry season, consistent with enhanced post-sunset uplift and plasma bubble formation during these periods.

A rare and important finding was the observation of strong midday scintillation on August 2 and 3 (2024). These events occurred outside the normal post-sunset period and coincided with significant degradation in PPP accuracy. The occurrence of such midday disturbances, also reported in other equatorial regions, suggests that solar and atmospheric processes can occasionally generate strong ionospheric irregularities during daytime under favorable conditions. The link between scintillation intensity and PPP performance observed in this study provides direct experimental evidence of how amplitude fluctuations in GNSS signals can affect positioning accuracy in low-latitude regions. These findings are significant for GNSS-based operations such as geodetic surveying, autonomous navigation, and timing applications, where millimetre-level precision is required.

This research contributes new knowledge in several ways. It provides the first documented evidence of strong midday scintillation over Nigeria, demonstrating that ionospheric irregularities can occur beyond the well-known evening hours. It establishes a quantitative relationship between the S4 and PPP positioning accuracy, which can be used to assess GNSS performance under disturbed ionospheric conditions. Finally, it delivers a locally validated dataset and seasonal reference for ionospheric scintillation in the Nigerian sector of West Africa, which can support future modelling, prediction, and mitigation strategies.

Future research should employ higher-rate GNSS sampling for ionospheric investigations and extend similar analyses across multiple constellations and successive solar cycles to enhance regional scintillation prediction models. Operationally, GNSS-based applications in low-latitude regions are encouraged to integrate high-resolution scintillation monitoring into their workflows to mitigate positioning errors, particularly during equinoctial months and post-sunset periods when ionospheric activity is most intense. For GNSS users in Nigeria and other equatorial regions, these findings are important. They show that high-precision applications such as surveying, mapping, and timing should either be scheduled outside peak scintillation periods or implemented with robust mitigation techniques.

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