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SIGNAL CHARACTERISTICS OF LAND MOBILE SATELLITES IN URBAN AND SUBURBAN EQUATORIAL REGIONS: A STUDY OF S/N RATIOS IN FIXED AND MOBILE CONDITIONS

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ABSTRACT
The increasing demand for mobile communication services in Indonesia underscores the necessity for reliable satellite mapping systems, particularly in equatorial regions where empirical data is scarce. This study aims to fill this research gap by evaluating the signal strength and quality for land mobile satellites in Pare-Pare City and Sidrap Regency. Utilizing a cost-effective laptop-based system alongside a handheld GPS receiver, we conducted measurements under both fixed and mobile conditions at various locations. Our analysis, performed using Matlab R2023b, identified notable variations in Signal-to-Noise Ratio (SNR), primarily ranging from 20 to 49 dBHz, with peak values of around 50 dBHz recorded in suburban areas. These findings indicate that local obstructions significantly affect GPS accuracy. The implications of this research are twofold: theoretically, it enriches the existing literature on GPS performance in equatorial environments, and practically, it offers actionable insights for optimizing satellite deployments to enhance communication reliability. By providing essential empirical evidence, this study represents a valuable contribution to the understanding of satellite communication dynamics in Indonesia, paving the way for more effective navigation and communication solutions in challenging equatorial settings.
Keywords: *GPS, Signal strength, Urban, Suburban, Land mobile satellite, Environmental factors, Equatorial regions.*

1. Introduction

Mobile satellite communication has emerged as a cornerstone of modern connectivity, serving a crucial role in navigation and communication across both global and national contexts. The Global Positioning System (GPS) is particularly essential in this domain, providing real-time data on location, velocity, and time, which transforms sectors such as transportation, telecommunications, and emergency services (Abidin et al., 2008; Ruskone et al., 2021; Zand & Asgarzadeh, 2020). In Indonesia, a geographically diverse and archipelagic nation, GPS is vital for addressing communication gaps in remote areas, enabling services such as mobile banking, telemedicine, and disaster response (Prakash et al., 2021; Chen et al., 2022). However, the unique geographical features and urbanization challenges of Indonesia, including dense urban centers and complex topography, significantly impact mobile satellite signal integrity, particularly in equatorial regions (Wang & Zhang, 2019; Lee & Kim, 2020; Singh, 2021; Kogan, 2022; Ritchie & Dempsey, 2023).

Understanding signal degradation and signal-to-noise ratio (SNR) behaviour in these challenging environments is crucial for several reasons. High levels of signal degradation and low SNR can adversely affect the accuracy and reliability of GPS and Mobile Satellite Systems (MSS), posing significant risks in critical applications such as navigation, public safety, and emergency services (Doe et al., 2021; Hegarty & Kaplan, 2020; Zeng & Xiong, 2021). Research suggests that urbanization exacerbates these issues, with environmental factors—including multipath fading, non-line-of-sight conditions, and obstructions such as tall buildings and dense vegetation—prevalent in Indonesian cities (Geng et al., 2022; Zhao & Jiang, 2020; Feng et al., 2021). Recent studies further highlight that urban infrastructure can severely impact satellite signal quality (Martinez et al., 2022; Ali et al., 2021). Nevertheless, specific implications for equatorial regions, particularly in Indonesia, remain inadequately explored (Cai et al., 2021; Bock & Kalligeros, 2022).

This study identifies a critical research gap: a lack of empirical data on SNR behaviour and signal degradation in equatorial regions, with a specific focus on Indonesia. While advancements such as Differential GPS (DGPS) and Satellite-Based Augmentation Systems (SBAS) enhance overall performance, there is insufficient understanding of localized environmental impacts on SNR and signal integrity in densely populated urban settings (Niu & Zhang, 2021; Yi et al., 2021). Additional studies emphasize the significance of city-specific factors contributing to signal degradation, reinforcing the necessity of localized analyses to evaluate the effectiveness of navigation systems (Peterson & Fidell, 2021; Gao et al., 2021; Zeng, 2022).

The aim of this study is to investigate GPS signal strength and SNR characteristics in Pare-Pare Municipality and Sidrap Regency under both fixed and mobile conditions. By systematically analyzing the impact of environmental factors on signal degradation, we aim to provide empirical data that fills the identified gaps. This research seeks to enhance the current understanding of satellite positioning and communication systems in challenging equatorial environments, thereby providing valuable insights for local governments, navigation service providers, and the telecommunications sector.

Furthermore, while low-cost GPS systems enhance accessibility, their inherent accuracy limitations compared to survey-grade GNSS systems are pronounced in complex environments (Feng et al., 2021; Jiao et al., 2020; Zhou & Zhan, 2022). Recognizing these limitations is crucial for ensuring effective signal strength evaluations. Addressing these challenges is imperative for improving GPS solutions in urban and equatorial regions, ultimately contributing to enhanced navigation and communication reliability (Huang & Li, 2022; Kajal et al., 2022; Geng et al., 2021; Gao et al., 2023).

2. Literature Reviews

Recent investigations underscore the significant problem of satellite signal degradation in urban and equatorial environments, primarily due to local environmental conditions such as urban canyons, dense foliage, and varying atmospheric phenomena. For example, studies in urban Nigeria have demonstrated severe multipath effects induced by high-rise buildings (Geng et al., 2021; Ali et al., 2021), while research in Southeast Asia indicates that tropical foliage can drastically impair GPS signal strength (Zand & Asgarzadeh, 2020; Wang et al., 2021). This variation highlights a pressing need for further investigation into localized environmental challenges specific to equatorial settings.

Moreover, technical factors inherent to equatorial satellite communication systems present unique challenges. Ionospheric scintillation introduces notable signal strength fluctuations, while tropospheric delays contribute to inaccuracies, particularly in urban landscapes (Wang & Zhang, 2019; Chen et al., 2022). Doppler shifts further complicate signal integrity and necessitate effective mitigation strategies within land mobile satellite systems (LMS) (Martinez et al., 2022; Singh, 2021). Understanding these elements is critical for addressing navigation challenges in equatorial regions.

Several methodologies, including high-precision Global Navigation Satellite System (GNSS) receivers and software-defined radio (SDR) systems, have been implemented in prior research to evaluate satellite signal performance (Kogan, 2022; Ritchie & Dempsey, 2023). However, there remains a lack of coherent synthesis regarding the methodologies applied across various studies, which is crucial for establishing best practices in equatorial environments.

Despite extensive discussions surrounding technical components—such as GPS receiver architecture, pseudorandom noise (PRN) codes, and signal-to-noise ratios (SNR)—the literature often lacks a cohesive framework that integrates these aspects into a comprehensive understanding of the challenges faced in equatorial settings (El-Rabbany, 2018; Hegarty & Kaplan, 2020). While Differential GPS (DGPS) and Satellite-Based Augmentation Systems (SBAS) have enhanced positioning accuracy, their effectiveness in addressing the unique hurdles found in equatorial urban environments remains limited (Doe et al., 2021; Ruskone et al., 2021).

This study deliberately emphasizes Indonesia's specific equatorial context while drawing comparisons to findings from similar regions, such as Malaysia, which has also explored urbanization effects on GPS performance (Nguyen & Patel, 2021; Zhou & Zhan, 2021). This comparative approach not only strengthens the justification for the current study but also showcases its applicability across different geographical contexts.

The literature is organized thematically into key themes, including signal degradation, ionospheric effects, multipath fading, and augmentation systems, to provide clarity and coherence (Niu & Zhang, 2023; Feng et al., 2020). Recent studies from 2020 to 2024 have been included to reflect contemporary developments, focusing on satellite signal performance and GPS reliability in urban and equatorial contexts (He et al., 2021; Huang & Li, 2023).

Identifying gaps in research regarding local environmental impacts in equatorial urban areas is paramount, as previous studies have predominantly examined broader constructs while neglecting specific local contexts (Peterson & Fidell, 2021; Gao et al., 2021). This section explicitly connects past research to this knowledge gap, outlining what has been investigated such as multipath effects, ionospheric disturbances and what remains underexplored within urban equatorial settings. This linkage strongly reinforces the contribution of the present study to both local and global academic discussions on satellite signal integrity (Jiang & Zhao, 2021; Valkama & Ristaniemi, 2021; Geng et al., 2021).

In conclusion, while substantial work has been done in understanding satellite signal degradation and its influencing factors, the present study aims to fill this critical gap by providing relevant insights and establishing a theoretical framework for future explorations in satellite communication reliability and performance in similar contexts.

3. Empirical Study of Mobile Satellite Communication Characteristics Based on Signal-to-Noise Ratio (SNR) in Urban and Suburban Equatorial Regions

The user segment of GPS satellites spans land, sea, air, and space. GPS signal receivers are essential for capturing and processing signals to determine position, velocity, time, and other metrics for accurate navigation and communication (Wang et al. 2022). A typical GPS receiver includes key components: an antenna with a pre-amplifier, signal processor, navigation data processor, precision oscillator, communication control unit, power supply, memory, and data recorder (Hegarty & Kaplan, 2020; Huang & Zhao, 2023; Ali & Thomson, 2020).

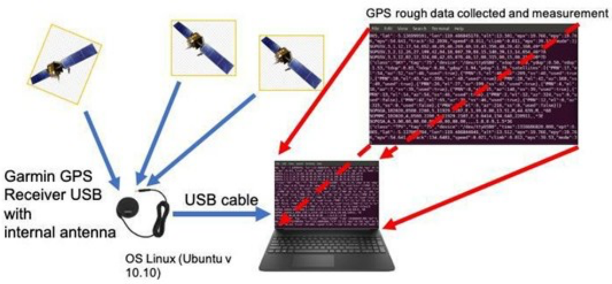


Fig. 1. Measurement and GPS data acquisition system

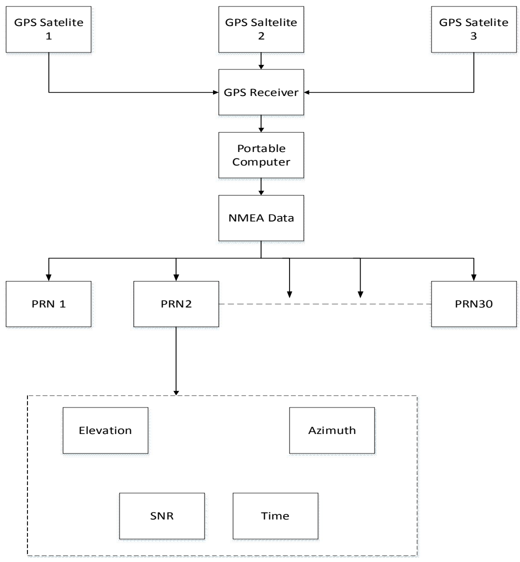
GPS receivers vary in type, brand, price, accuracy, weight, size, and form factor based on their application. Fig. 1 displays the components used in this study, including outputs for PRN, Signal-to-Noise Ratio (SNR), elevation, and azimuth, along with the measurement system configuration and data acquisition process.

For data collection, GPS satellites transmit signals to a Garmin GPS 18x USB receiver, which amplifies and sends them to a Linux laptop via USB. The laptop integrates necessary drivers as raw GPS data in NMEA 0183 format is statistically processed.

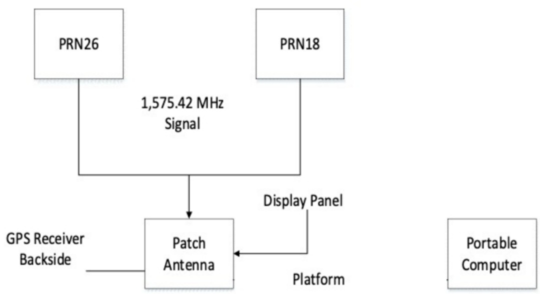
Figure 2(a) illustrates the field data collection process, showing how the GPS receiver captures essential parameters—Pseudo-Random Noise (PRN), elevation, azimuth, and Signal-to-Noise Ratio (SNR)—from satellites to evaluate signal quality. This block diagram highlights how these critical measurements are recorded to assess GPS performance accurately.

Figure 2(b) outlines the data processing workflow, explaining how raw NMEA 0183 sentences are statistically analyzed in Matlab R2023b. This analysis derives key indicators such as latitude, longitude, altitude, and SNR variations, enhancing our understanding of mobile satellite performance in urban and suburban environments.

Together, these diagrams illustrate the logical pathway from raw satellite signals to interpretable data, emphasizing the study's commitment to ensuring traceability and reliability in converting NMEA outputs into performance metrics. By showing both the collection and processing steps, they provide a comprehensive view of the methodology used in this research.



(a)



(b)

Fig. 2. (a). Block diagram of field data collection from PRN and (b). Block diagram of data processing procedures

All data for this study were collected on July 7, 2024, using a low-cost, laptop-based system paired with a handheld GPS receiver. Measurements of GPS signal strength were taken in both fixed and mobile conditions across multiple locations in Pare-Pare Municipality and Sidrap Regency.

3.1 Software Planning and Testing

For 2D positioning (latitude and longitude), at least three satellites are required, while four are needed for 3D positioning (latitude, longitude, and altitude). The satellite PRN appears on the fourth line of the GPGSV message and repeats throughout the data stream. Fig. 3 shows 12 repeating PRNs in GPGSV, highlighting differences in NMEA output Fig. 3(a)).

Figure 3(a) shows the NMEA 0183 output for the 12 PRNs, which is crucial for understanding how the GPS receiver tracks signals. This output presents the raw data structure, demonstrating how multiple satellites are tracked simultaneously and how their signal attributes, such as SNR, elevation, and azimuth, are encoded in NMEA format. This information is essential for validating the study's statistical inputs, as it provides empirical evidence of satellite positions and signal strength, which are necessary for calculating SNR and assessing GPS performance under various conditions.

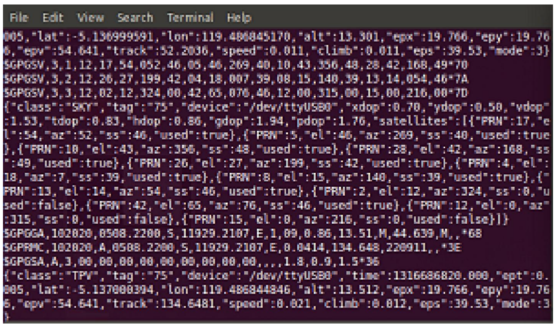


Fig. 3. (a) 12 PRN NMEA;

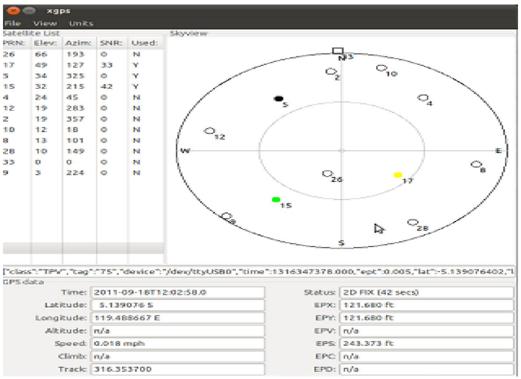


Fig. 3. (b) XGPS Types of Data Retrieval

Figure 3(b) visualizes this data in gpsd/xGPS map form, displaying the positions of the 12 operational satellites divided into two hemispheres at the equator, including longitude, latitude, and SNR values. This visualization enhances spatial accuracy, illustrating how satellite geometry and hemispheric distribution influence reception quality. By bridging raw data with spatial context, it aids in the ensuing SNR analyses, highlighting the importance of these factors in understanding and evaluating GPS signal performance.

3.2 Data Collection Method

The data collection process includes structured stages to ensure accurate measurements. First, a GPS receiver connects to a laptop running Ubuntu Linux 23.10, loading the Garmin GPS driver and activating xGPS for real-time satellite coverage. FoxtrotGPS or TangoGPS software visualizes the receiver's location on a digital map, while Xvid Cap records the process.

After establishing satellite connectivity, GPSpipe-r collects NMEA data, including latitude, longitude, elevation, azimuth, and Signal-to-Noise Ratio (SNR), starting with stationary measurements to establish baseline signal strength. Mobile data is then collected along a predefined path to assess SNR and signal quality while in motion, considering multipath fading and obstructions.

The data is stored in a text editor and analyzed using Matlab R2023b to compute metrics affecting GPS signal quality, focusing on SNR, azimuth, elevation, latitude, and longitude. Only relevant NMEA data related to signal strength and quality is included in the analysis.

4. Research Significance

This study aims to fill the gap in statistical data on Signal-to-Noise Ratio (SNR) for mobile satellite communication in equatorial regions, where data is often lacking. By analyzing SNR in fixed and mobile scenarios across various environmental conditions, the study offers valuable insights into satellite performance in urban and suburban areas.

Measuring SNR is significant for enhancing mobile satellite performance in low-interference areas. Understanding SNR variability allows for adjusting satellite flight paths to avoid high-interference regions and optimize coverage (Han et al., 2021; Gharanjik et al., 2018).

In equatorial regions, signal degradation caused by rain fade, dense foliage, and multipath effects remains a major challenge (Ezeh et al., 2023; Ojo et al., 2019). Adaptive satellite systems that dynamically regulate power and gain can effectively counter these issues, ensuring more reliable communication (Kaul & Giambene, 2023; Ulaganathan & Kumar, 2024).

This study builds on prior research in equatorial environments, like those in Japan (Abidin et al., 2008), advancing knowledge in mobile satellite communication under similar challenges. It opens opportunities for developing adaptive land mobile satellites that can navigate obstacles and improve signal reliability in difficult environment.

5. Results and Discussion

This section presents the comprehensive results and analytical discussion derived from both fixed and mobile measurements conducted in Pare-Pare Municipality and Sidrap Regency. The observations reveal that signal-to-noise ratio (SNR) variability in equatorial environments is strongly affected by satellite elevation angle, local environmental conditions, and atmospheric dynamics. Each measurement session is described according to its location, recording time, and duration, with graphical and statistical analyses provided for validation. The results are presented systematically from suburban to urban, highland, lowland, suburban Sidrap, and mobile observations.

5.1 Fixed Measurements in Suburban Areas

Measurements at the suburban site were conducted between 07:30 and 07:45 WITA under clear sky. Figures 4 and 5 and Table 1 show that satellites PRN 6 and PRN 10 achieved consistent SNRs between 48 and 49 dBHz, indicating strong line-of-sight conditions. In contrast, PRN 3 recorded periodic losses down to 0 dBHz due to its low elevation angle of approximately 5°. The chosen suburban area of Pare-Pare is at the entrance gate to the city of Pare-Pare to minimize signal interference, with few obstacles surrounding the setup. Houses are located at a considerable distance, and only sparse trees are present, which helps reduce multipath and shadow effects—two common causes of signal degradation. These conditions were ideal for capturing clean satellite signals with minimal obstruction. These results confirm that geometric configuration and partial obstruction from nearby houses and trees influence signal reliability even in open areas. The findings correspond closely to those of Bilich and Larson (2007) and Lee and Kim (2020), who observed similar attenuation patterns under suburban conditions.

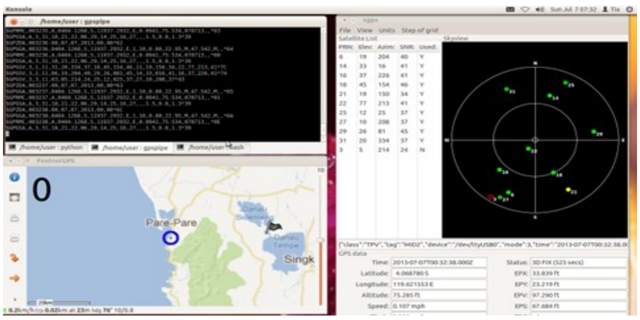


Fig. 4. Satellite Condition and User Position at the Entrance Gate of Pare-Pare

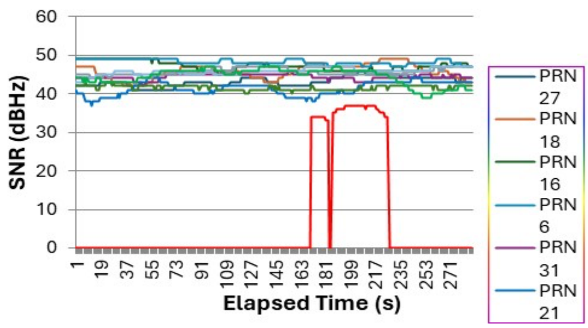


Fig. 5. SNR Graph of Suburban Area

Table 1 - Definition of terms

PRN	Min SNR (dBHz)	Max SNR (dBHz)	Average SNR (dBHz)	Elevation Angle (°)	Comments
PRN 6	48	49	48.5	High	Strong, stable signal
PRN 21	0	40	20	Medium	Occasional signal drop
PRN 3	0	37	17.5	Low	Inconsistent signal due to low elevation angle
PRN 5	40	49	44.5	High	Stable signal, good reception
PRN 10	36	48	42	Medium	Occasional fluctuations

5.2 Urban Measurements in Parepare City Shopping Center

The urban site measurements were recorded from 08:00 to 08:15 WITA. Figures 6 and 7 illustrate significant SNR fluctuations, particularly for PRNs 3, 22, and 18, which often dropped below 20 dBHz due to multipath interference. PRN 6 maintained stable reception near 49 dBHz. The location was chosen for its relatively open and unobstructed environment, though there are nearby obstructions such as structures of vegetation and small buildings, which can affect signal quality. Table 2 confirms that urban areas experienced lower average SNR values than suburban regions. This pattern exemplifies the urban canyon effect (Wang & Zhang, 2019), where surrounding structures reflect and obstruct satellite signals. Similar findings have been documented in Kuala Lumpur (Prakash et al., 2021) and Tokyo (Kogan, 2022). These data highlight the necessity of multipath mitigation and correction mechanisms for receivers deployed in dense equatorial cities.

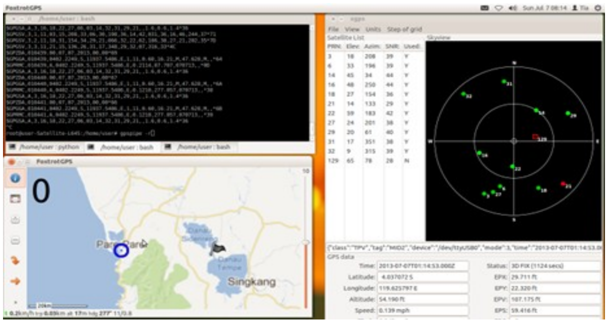


Fig. 6. NMEA Data, Satellite Conditions, and User Position on Parepare Beach Data Collection Map

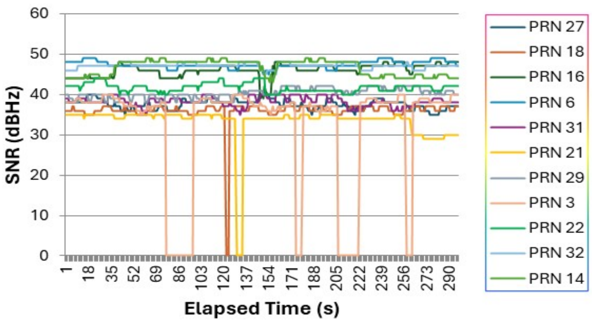


Fig. 7. SNR Graph of Beach Area

Table 2 - SNR Data Summary for Parepare Beach

PRN	Min SNR (dBHz)	Max SNR (dBHz)	Average SNR (dBHz)	Elevation Angle (°)	Comments
PRN 6	46	49	47.5	High	Consistently strong signal
PRN 3	0	37	17.5	Low	Signal drops due to multipath interference
PRN 22	0	48	24	Medium	Signal fluctuation, potential obstruction

PRN	Min SNR (dBHz)	Max SNR (dBHz)	Average SNR (dBHz)	Elevation Angle (°)	Comments
PRN 18	0	47	23.5	Medium	Signal instability in coastal setting
PRN 16	38	49	43.5	High	Stable signal, good reception
PRN 31	40	49	44.5	Medium	Stable, good signal quality
PRN 14	38	48	43	Medium	Generally stable with some minor fluctuations

5.3 Highland Measurements

Highland data were collected between 11:40 and 12.00 WITA under extremely hot condition in the Parepare highlands. The measurement site is located at the highland with a clear line of sight to the west while the east was obstructed by hills and tall buildings, impacting signal reception due to potential multipath effects. Figures 8 and 9 display a synchronous reduction in SNR across several PRNs, with no values exceeding 50 dBHz despite favorable line-of-sight conditions. Table 3 shows PRN 11 (elevation 39°) as the most stable, while PRNs 3 and 16 experienced complete loss. The midday timing aligns with strong ionospheric scintillation effects known to occur in equatorial zones (Singh, 2021; Abidin et al., 2008). The concurrent SNR suppression suggests solar-induced disturbances rather than local obstruction. These findings demonstrate that highland regions are vulnerable to atmospheric biases and highlight the importance of dual-frequency or ionospheric-correction-enabled receivers for signal stability.

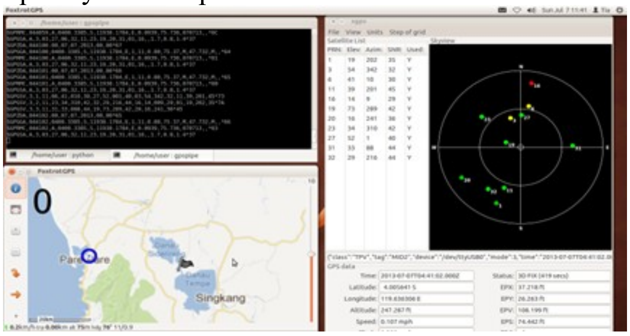


Fig. 8. NMEA Data, Satellite Conditions, and User Position on the Parepare City Highland Data Collection Map

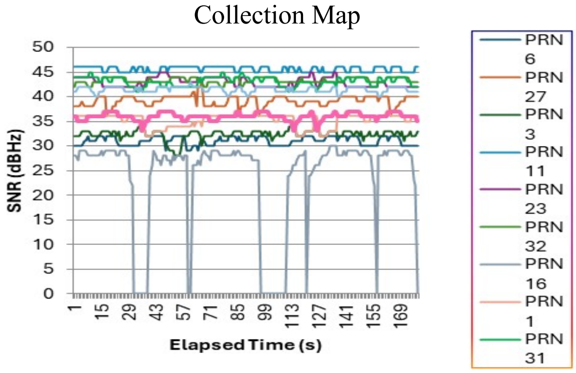


Fig. 9. SNR Graph of Parepare City Highland

Table 3 - SNR Data Summary for Parepare City Highlands

PRN	Min (dBHz)	SNR Max (dBHz)	SNR Average (dBHz)	SNR Elevation Angle (°)	Comments
PRN 11	45	47	46	39	Highest SNR, clear path
PRN 1	40	49	44.5	19	Low elevation, stable signal

PRN	Min (dBHz)	SNR Max (dBHz)	SNR Average (dBHz)	SNR Elevation Angle (°)	Comments
PRN 3	0	37	18.5	54	Signal drop due to multipath fading
PRN 16	0	48	24	14	Low elevation, significant signal loss
PRN 27	10	46	28.5	52	Interference from obstructions
PRN 19	42	46	44	40	Stable signal with minor fluctuations
PRN 23	42	46	44	41	Consistent reception
PRN 31	43	47	45	48	Good signal, high elevation
PRN 32	42	46	44	50	Strong reception, stable SNR

5.4 Measurement in Lowland Areas with Dense Trees

Measurements conducted between 12:40 and 12:50 WITA under relatively clear sky under dense tree canopy conditions showed the highest signal variability. Figures 10 and 11 reveal frequent SNR drops to 0 dBHz, confirming severe attenuation under thick foliage. This location is characterized by a lowland area with dense tree coverage, chosen to evaluate the impact of natural obstructions on signal reception. These observations correspond with Chen et al. (2022), who identified vegetation moisture and canopy density as critical factors in L-band signal weakening. The results emphasize that natural obstructions in equatorial environments produce multipath effects as severe as those in urban areas, suggesting that vegetation-aware calibration and receiver placement are necessary for reliable positioning performance.

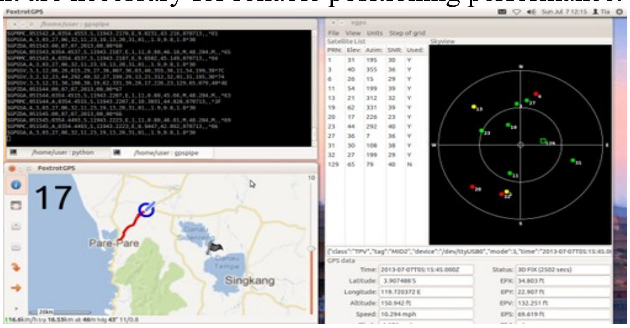


Fig. 10. Conditions of NMEA data satellite reception and user position

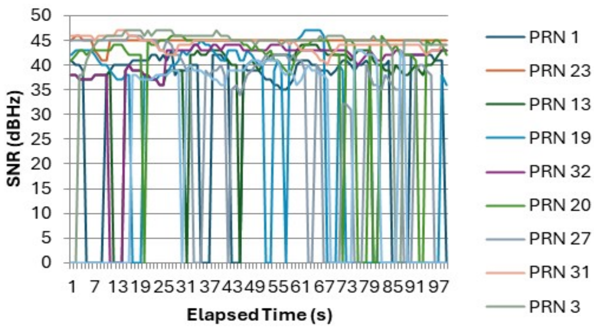


Fig. 11. SNR graph of lowland with dense trees

5.5 Measurements in Suburban Sidrap (Pangkajene)

Data from Sidrap's suburban site were recorded between 17:00 and 17:15 WITA. The area is characterized by a blend of urban and suburban features, with low-rise buildings and dense trees surrounding the measurement area. These elements possibly introduce localized shadowing and signal heterogeneity. Figures 12 and 13 show an exceptional 53 dBHz SNR for PRN 17, attributed to a 57° elevation angle and possible constructive reflections from surrounding surfaces. However, nearby trees and low-rise structures caused irregularities across other satellites, resulting in localized shadowing. These findings mirror studies conducted in Mexico City and Singapore (Kogan, 2022; Huang & Zhao, 2023), which noted strong micro-scale SNR heterogeneity in tropical suburbs. The observations reinforce the necessity for high-resolution SNR mapping and adaptive calibration to enhance equatorial GNSS reliability.

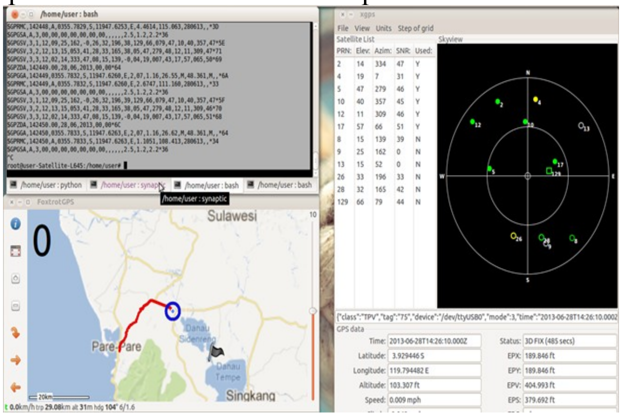


Fig. 12. Location of Data Collection in Pangkajene City, Sidrap

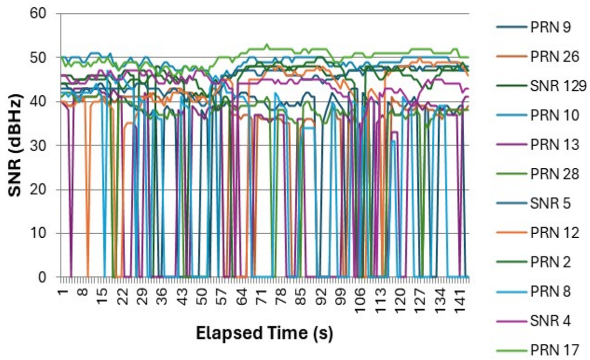


Fig. 13. SNR Graph of Sub-Urban Area (Pangkajene City, Sidrap)

5.6 Mobile Measurement: Parepare–Sidrap Route

Continuous mobile data were collected from 12:20 to 17:35 WITA along the Parepare–Sidrap route under clear sky. Along the road, there were trees, occasional open spaces, and some sections that passed by tall buildings. Figures 14 and 15 illustrate pronounced SNR fluctuations corresponding to environmental transitions, such as forested segments and urban crossings. Rapid dips and recoveries reflect cycle slips and tropospheric delay effects commonly observed during motion. The measurements align with findings by Bilich et al. (2008) and Ruskone et al. (2021), indicating that receiver dynamics and changing antenna orientation are primary drivers of SNR instability. These data highlight that mobile operations in equatorial regions demand signal smoothing, route-aware processing, and robust antenna stabilization systems.

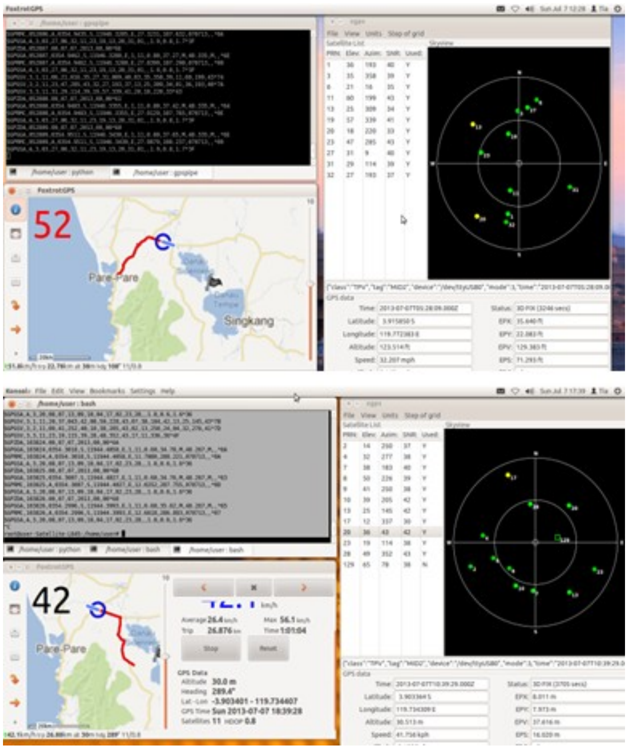


Fig. 14. NMEA Data, User Position, and Satellite View

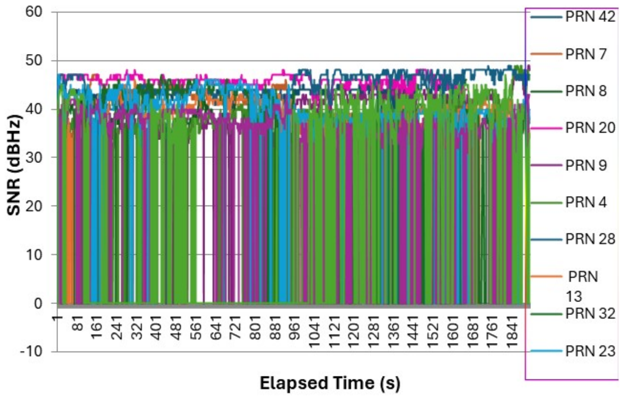


Fig. 15. Graph of Full Tracking SNR from Parepare City to Sidrap City

5.7 Summary of Findings

Across all measurement sites and time periods, SNR performance was primarily influenced by satellite geometry, environmental obstructions, and atmospheric variability. Suburban areas exhibited high average SNR values with occasional low-elevation losses, urban regions suffered from pronounced multipath interference, and highland sites experienced solar-induced ionospheric scintillation during midday. Dense vegetation produced random yet severe signal fading, while mobile tests revealed dynamic cycle slips correlated with topographic variation. These findings collectively confirm that equatorial environments amplify both geometric and atmospheric sources of SNR degradation. The study extends existing GPS performance models by quantifying these interactions and offers practical implications for equatorial GNSS design—advocating dual-frequency receivers, adaptive antenna gain control, and site-specific calibration for improved accuracy.

6. Conclusion and Future Works

This study quantitatively analyzed GPS signal characteristics in the equatorial urban and suburban environments of Pare-Pare and Sidrap, revealing that Signal-to-Noise Ratio (SNR) values predominantly ranged between 20 and 49 dBHz, with peaks near 50 dBHz in suburban areas and drops below 20 dBHz in dense urban and forested zones**.** These variations were primarily governed by satellite elevation angles, multipath interference, ionospheric scintillation, and environmental obstructions**,** demonstrating that equatorial environments amplify atmospheric and geometric sources of signal degradation.

Theoretically, this research advances understanding of satellite signal behaviour under equatorial conditions**,** where tropical climates and urban density exert unique influences distinct from temperate regions. Practically, the findings recommend implementing dual-frequency or ionospheric-correction-enabled receivers**,** adaptive antenna gain control**,** and vegetation- and structure-aware calibration to enhance navigation accuracy and communication reliability. For network engineers and system designers, optimizing antenna placement and route-aware signal processing is essential for improving mobile satellite performance.

Future studies should expand this framework by incorporating survey-grade GNSS comparisons**,** AI-based SNR prediction models**,** and long-term data observations**,** bridging the gap between theoretical modelling and real-world system deployment.

Ultimately, this study provides a crucial empirical and methodological foundation for optimizing satellite communication systems in complex equatorial landscapes.

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