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The influence of tree canopy on GPS positioning accuracy

Saulius Japertas[1,2,3] & Marius Mažeika[1,3]✉

Accurate outdoor localization in vegetation-rich environments remains a significant challenge for satellite-based positioning systems. Tree canopy and dense foliage degrade GPS signal quality and may considerably reduce positioning accuracy, especially in applications related to smart mobility and assistive navigation systems. This study investigates the influence of tree canopy on GPS positioning accuracy in a park environment using a smartphone-based GNSS receiver. Experimental measurements were performed at five locations under two different seasonal conditions: with foliage and without foliage. The obtained positioning data were analyzed using several statistical indicators, including variance, cumulative distribution functions (CDF), Circular Error Probability (CEP), R95, DRMS, and carrier-to-noise ratio (C/N). The results showed that positioning errors in the presence of foliage were between 1.86 and 3.66 times higher compared to measurements performed without foliage at most measurement positions. Average positioning variance increased from 1.54 m^2 without foliage to 5.99 m^2 with foliage. In addition, foliage reduced the carrier-to-noise ratio of received satellite signals, and C/N values below 30 dB-Hz were observed more frequently in dense canopy conditions. The results also indicate that foliage has a stronger influence on signal quality than on the number of visible satellites. The obtained results confirm that tree canopy significantly affects GPS localization accuracy and signal reliability in outdoor environments. The study contributes to a better understanding of GNSS performance degradation in vegetation-rich areas and may be useful in the development of outdoor assistive mobility and navigation systems.

Keywords GPS localization, Outdoor environments, Assistive mobility, Positioning accuracy

Accurate outdoor localization has become an essential component of modern navigation, monitoring, and assistive mobility systems. Global Navigation Satellite Systems (GNSS), including the Global Positioning System (GPS), are widely used in applications requiring reliable positioning and tracking. Such applications include pedestrian navigation, autonomous mobility support, environmental monitoring, emergency response systems, and assistive technologies for elderly and disabled individuals. In recent years, increasing attention has been devoted to smart mobility solutions, such as intelligent electric rollators and other assistive devices, which require continuous and reliable localization in complex outdoor environments.

However, accurate GPS positioning remains a significant challenge in areas with dense vegetation and tree canopy. Forested and park environments often degrade satellite signal quality due to signal attenuation, multipath propagation, and partial obstruction of satellite visibility. These effects reduce positioning accuracy and may negatively influence the reliability of navigation systems operating in such environments. The problem becomes especially important in safety-critical scenarios involving vulnerable users, such as elderly individuals with reduced mobility, cognitively impaired persons, or situations requiring rapid localization of lost children or pets.

Previous studies have shown that vegetation density, foliage conditions, seasonal variations, and forest structure significantly influence GNSS performance[1–13]. Signal attenuation caused by leaves and branches reduces carrier-to-noise ratios, while reflections from vegetation and surrounding objects introduce multipath errors that increase positioning uncertainty. Several studies have also demonstrated that positioning accuracy may vary substantially depending on canopy density, satellite geometry, environmental conditions, and the type of GNSS receiver used. Recent research additionally highlights the growing capabilities of modern smartphones and low-cost GNSS receivers in outdoor positioning applications[14–23].

Although numerous studies have investigated GNSS performance in forested environments, relatively limited attention has been devoted to comparative analysis of positioning accuracy under identical conditions with and

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without foliage, particularly using commonly available smartphone-based GNSS solutions. Furthermore, the implications of such positioning errors for assistive mobility systems operating in parks and vegetation-rich environments remain insufficiently discussed.

Therefore, this study investigates the influence of tree canopy and foliage on GPS positioning accuracy in a park environment. Experimental measurements were performed during periods with and without foliage using the same measurement locations, receiver, and measurement procedures. The obtained data were analyzed using several statistical and positioning accuracy indicators, including variance, cumulative distribution functions (CDF), Circular Error Probability (CEP), R95, DRMS, and carrier-to-noise ratio (C/N) analysis. The results provide insight into the impact of vegetation on GPS localization performance and contribute to improving the reliability of outdoor assistive mobility and navigation systems operating in complex environmental conditions.

Literature analysis

Forests and vegetation can significantly affect GPS reception and accuracy due to a complex interplay of physical factors[1–5]. Analysis of existing research indicates that the primary mechanisms influencing signal quality include: Signal Attenuation and Absorption: Vegetation acts as a dielectric medium; leaves, branches, and trunks contain water that absorbs radio frequency signals in the L-band (1.2 GHz and 1.5 GHz). This attenuation is most severe in dense rainforests or during wet conditions, where high water content leads to significant signal weakening or complete loss. Multipath Interference: Forest environments are prone to multi-beam transmissions. GPS signals reflect off tree canopies and the ground surface, especially on wet or uneven forest floors. When a receiver captures both direct and reflected signals, a delay is introduced, leading to erroneous position calculations[1,6]. Signal Blocking and Geometry: Dense foliage, particularly in jungle areas, can obstruct the line-of-sight between the receiver and satellites. This reduces the number of visible satellites, causing a deterioration in the Geometric Dilution of Precision (GDOP) and making it difficult for the device to calculate an exact position[4,7]. Temporal and Seasonal Dynamics: In deciduous forests, signal quality varies seasonally, often improving in winter after leaf-fall and deteriorating during the peak growth of spring and summer[5,8]. Empirical studies have quantified these effects through various field experiments. In[1], comparisons between a pine forest and a logged area showed that standard deviations for baselines and height differences improved by 50–70% after logging. Notably, the height component's accuracy remained 2 to 4 times lower than horizontal accuracy. Research in[2] utilized 17 different forest locations to test autonomous and differential GPS techniques over 7-day periods, concluding that accuracy varies significantly based on specific canopy characteristics, leading to practical recommendations for forestry professionals. Comparative studies of hardware have also revealed surprising results. In[3], a smartphone (iPhone 12 Pro) demonstrated positional errors significantly lower than some professional Garmin receivers and comparable to high-end Trimble devices, confirming that forest variables impact all GNSS receivers regardless of their class. To address these errors, researchers in[4] employed Recurrent Neural Networks (RNNs) to develop mathematical models. Their findings emphasized that variables related to the forest canopy are the most influential factors in predicting GPS measurement accuracy. Further research highlights the influence of movement and density. In[5], a study involving a car moving at 20 km/h found that the worst mean accuracy (56.10 m) occurred in autumn, while the best was recorded in spring. Moreover, canopy density directly correlates with the frequency of data updates; dense covers often lengthen scheduled update intervals[7]. Studies[8–11] further analyse these nuances, showing that signal-to-noise ratio (SNR) attenuation is tied to the Leaf Area Index (LAI) and that positioning accuracy can actually be better in deciduous forests compared to dense coniferous stands like spruce. Finally, even with geodetic-class receivers, significant differences in multipath values are observed under similar conditions, highlighting the inherent unpredictability of forest environments[6]. Beyond environmental factors, recent research has focused on the integration of hybrid sensor systems and the evolving capabilities of non-specialized hardware. For instance, study[12] demonstrates that even relatively inexpensive receivers, such as the u-blox ZED-F9P, can yield highly accurate results in forested areas (e.g., in Southern Finland) when integrated with LiDAR equipment. This suggests that sensor fusion can compensate for signal degradation caused by canopy density. The performance of different satellite constellations also varies significantly in wooded environments. Research in[13] investigated the COMPASS (BeiDou) system, revealing that its geostationary orbit satellites offer better prediction stability than traditional GPS. Specifically, BeiDou achieved improvement rates of approximately 85% in light foliage and 84% in heavy foliage, outperforming GPS which fluctuated between 70 and 73%. The study concluded that a multi-constellation approach (GPS+COMPASS) significantly reduces 3D root mean square errors, particularly in the vertical (up) coordinate, with overall accuracy improvements reaching up to 82–86%. A substantial body of literature[14–23] explores the gap between specialized GNSS receivers and modern smartphones. In[14], tests using an iPhone 6 in various lighting and foliage conditions showed that while seasons might not drastically change average horizontal errors, daylight observations during the leaf-loss season tend to be more precise. The iPhone's accuracy (7–13 m) was found to be comparable to recreational-grade GPS units, though it relied on Wi-Fi assistance to maintain this level. From a signal processing perspective, work[15] indicates that while vegetation-transmitted signals still follow Normal and Weibull distributions, their parameters shift significantly, complicating the modelling of Right-Hand and Left-Hand Circular Polarization (RHCP/LHCP). Comparative analyses continue to evaluate the reliability of smartphones as professional tools. While[16] found significant differences between smartphone raw data and DGPS, ANOVA tests suggested that for horizontal positioning, smartphones can serve as a viable alternative to handheld GPS receivers. High-end devices utilizing the P(L5) code can achieve remarkable 3D accuracy—approximately 0.4 m with 16 satellites and up to 0.3 m with 26 satellites, nearly matching DGPS performance[18]. However, large-scale crowdsourced studies[18] involving over 1000 users show that real-world accuracy is highly dependent on environment: ranging from 3.5–6.8 m in open spaces to 13–35 m near buildings. Further improvements in smartphone positioning are often achieved through external sensors or algorithmic constraints. Pairing a phone with a mid-priced external GNSS sensor significantly boosts performance compared to internal antennas[19]. In urban "building canyons,"

accuracy can be enhanced by using sidewalk edges as references and applying specific search algorithms to constrain GNSS drift[20]. Modern units like the Redmi K60 Ultra have shown that multi-frequency tracking noise and time-to-first-fix (TTFF) are now comparable to conventional receivers in urban open spaces[21]. For vehicular applications, real-time Precise Point Positioning (PPP) on smartphones can achieve horizontal accuracy of 1–1.5 m (RMS)[22]. Despite these advances, a 2021 review[23] emphasizes that working with raw smartphone observations remains challenging due to inherent hardware noise and data quality issues. Finally, the application of GNSS extends into social and healthcare domains, specifically for the mobility of the elderly and people with disabilities[24–26]. Review[24] identifies GPS as a core assistive technology for rehabilitation and daily life, though it highlights the need for more user-oriented, intelligent systems. Innovative solutions include scooter navigation systems that fuse GPS, WLAN, and inertial sensors to help seniors maintain independence[25], and specialized rollator-based systems that effectively guide users with cognitive impairments through real-world environments[26]. However, the use of these technologies raises critical ethical concerns. As noted in[27], researchers must navigate challenges regarding participant anonymity, "unintended" data collection, and the fears of vulnerable groups regarding constant monitoring and digital exclusion.

Research methodology

Positioning error evaluation

The objective of this study was to evaluate the influence of tree canopy and foliage on GPS positioning accuracy in a vegetation-rich outdoor environment. The analysis was based on a comparative approach, where measurements obtained during periods with foliage were compared with measurements performed under the same conditions after leaf fall.

The measured GPS coordinates were compared with reference coordinates obtained from Google Maps. Although these reference coordinates do not provide survey-grade geodetic precision, they allow consistent comparison of positioning deviations under different environmental conditions. Since the same reference positions were used throughout all experiments, the obtained deviations can be used to evaluate relative changes in localization accuracy caused by foliage conditions.

Positioning errors were determined as the deviation between the measured GPS coordinates and the corresponding reference positions. The obtained results were further analysed statistically in order to evaluate both average positioning accuracy and the dispersion of the measured data.

Statistical analysis of positioning accuracy

Several statistical indicators commonly used in GNSS positioning analysis were applied in this study. These parameters were selected in order to evaluate not only the average localization error but also the stability and distribution of positioning results.

The following parameters were calculated and analysed:

- Mean positioning error;
- Variance and standard deviation;
- Median values;
- Skewness and kurtosis coefficients;
- Cumulative distribution functions (CDF);
- Circular Error Probability (CEP);
- R95 parameter;
- Distance Root Mean Square (DRMS);
- 9th decile values.

The Distance Root Mean Square (DRMS) values reported in this study are expressed in metres (m) and represent the two-dimensional horizontal positioning accuracy.

In addition to positioning errors, several GNSS signal quality indicators were also analysed, including:

- Carrier-to-noise ratio (C/N);
- Number of visible satellites;
- Position Dilution of Precision (PDOP);
- Horizontal Dilution of Precision (HDOP);
- Vertical Dilution of Precision (VDOP);
- Satellite elevation and azimuth angles.

The obtained statistical parameters allowed evaluation of the influence of foliage on both positioning accuracy and GNSS signal quality.

Control of external GPS error sources

GPS positioning accuracy is influenced not only by vegetation and tree canopy but also by several other factors, including satellite clock and ephemeris errors, atmospheric effects, receiver noise, satellite geometry, and multipath propagation.

To reduce the influence of these external factors, the experiments with and without foliage were performed under identical conditions. Measurements were carried out at the same locations using the same smartphone receiver, the same software application, and identical measurement procedures. In addition, measurements in both cases were performed during periods with good satellite visibility and favorable weather conditions.



Fig. 1. Experimental area in Munich (Alter nördlicher Friedhof) and five GPS measurement positions. Base map: © OpenStreetMap contributors (ODbL 1.0; https://www.openstreetmap.org/copyright). Measurement positions were added by the authors using Microsoft Paint included with Microsoft Windows 10, version 22H2, OS build 19045.6456 (Microsoft Corporation; https://apps.microsoft.com/detail/9PCFS5B6T72H).

Position Number	Number of trees	Number of bushes
1	9	0
2	5	2
3	4	6
4	1	2
5	2	7

Table 1. Density of trees and bushes around the measurement positions.

The recorded PDOP, HDOP, and VDOP values remained very good throughout all experiments, while the number of visible satellites showed only minor variation between the two measurement periods. Therefore, it can be assumed that several common GPS error sources, such as satellite clock errors, ephemeris drift, receiver noise, and atmospheric delays, affected both measurement scenarios in a similar manner.

Consequently, the comparative analysis between measurements with foliage and without foliage allows the influence of tree canopy, signal attenuation, and canopy-related multipath effects to be considered the primary factors responsible for the observed differences in positioning accuracy.

Experimental setup

Measurement environment

The experiments were conducted in a small park area in Munich, Germany (Fig. 1). Five measurement positions were selected in locations with different densities of trees and bushes.

The density of trees and bushes taller than approximately 2 m within a radius of about 10 m around each measurement position is presented in Table 1.

The investigated area was mainly covered by deciduous trees and shrubs. Although some positions contained relatively small numbers of trees, the canopy density within the park area was sufficient to influence GPS signal propagation and reception conditions.

Measurement procedure

Two sets of measurements were performed under different seasonal conditions:

- Measurements with foliage were conducted on October 17 from 09:13 to 10:06;
- Measurements without foliage were conducted on December 21 from 11:03 to 11:27.

During the foliage measurements, ten positioning measurements were recorded at each position every 10 s. The first measurement campaign was intentionally designed with ten repeated observations in order to evaluate the repeatability and stability of the coordinate estimates. The analysis showed that the average coordinates

calculated from the first three measurements differed by less than 0.1% from the average obtained using all ten measurements. Therefore, three repeated measurements were considered sufficient for the second measurement campaign (without foliage). Consequently, three measurements were performed at each position, except for Position 1, where ten measurements were also recorded.

The same measurement positions and measurement procedures were used in both experimental cases to ensure comparability of the obtained results.

Equipment and recorded parameters

The measurements were performed using a Redmi Note 8T smartphone together with the open-source Android GNSS/GPS testing application "GPSTest".

The application provided the following recorded parameters:

- Measurement time;
- Geographic coordinates;
- Positioning altitude;
- Number of visible satellites;
- Carrier-to-noise ratio (C/N);
- PDOP, HDOP, and VDOP values;
- Satellite elevation and azimuth angles;
- Time to First Fix (TTFF).

The collected data were further processed and statistically analysed in order to evaluate the influence of tree canopy on GPS positioning accuracy and GNSS signal quality.

All measurements were performed by one of the authors (S. Japertas) during a research visit to Munich. No local individuals participated in the data collection. The measurements were carried out in publicly accessible park areas using a handheld smartphone GNSS receiver. No equipment was installed, no vegetation or infrastructure was disturbed, no personal data were collected, and no special permission or ethical approval was required.

Results

As expected, foliage had a significant influence on positioning errors (Figs. 2 and 3). In most measurement positions, the presence of foliage resulted in noticeably higher localization errors compared to measurements performed without foliage.

Position 1 differed from the general trend, as lower positioning errors were observed in the presence of foliage than in the absence of leaves. This may be explained by the proximity of the measurement location to a nearby wall (Fig. 1), which likely influenced multipath propagation conditions. In the absence of foliage, stronger signal reflections from the wall may have reached the receiver, increasing positioning errors. When foliage was present, vegetation located near the wall may have partially scattered or attenuated reflected signals, thereby reducing the influence of multipath effects.

Table 2 presents the average positioning errors measured at each experimental position under foliage and non-foliage conditions.

It should also be noted that the positioning errors at Position 1 remained relatively stable throughout the measurement period in both experimental cases. This is reflected in the variance values, which at Position 1 were between 1.1 and 17 times lower than those observed at the remaining measurement positions.

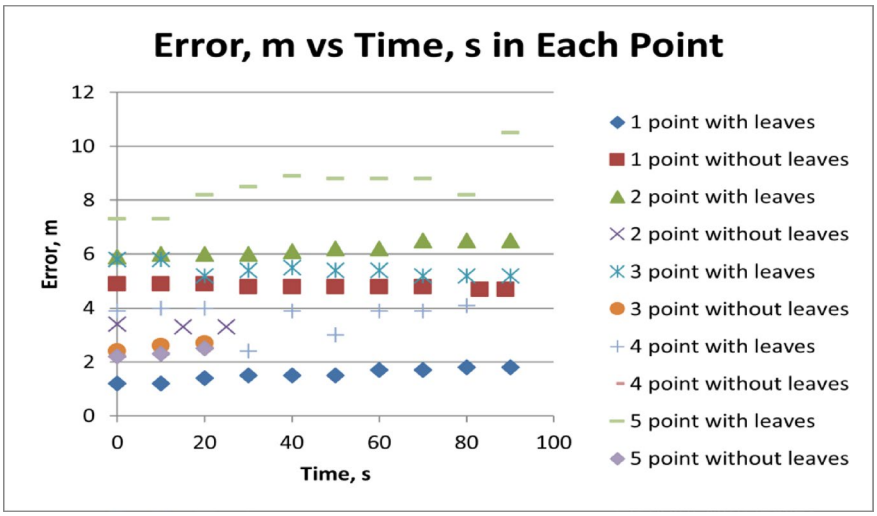


Fig. 2. Comparison of positioning errors measured at different locations under foliage and non-foliage conditions.

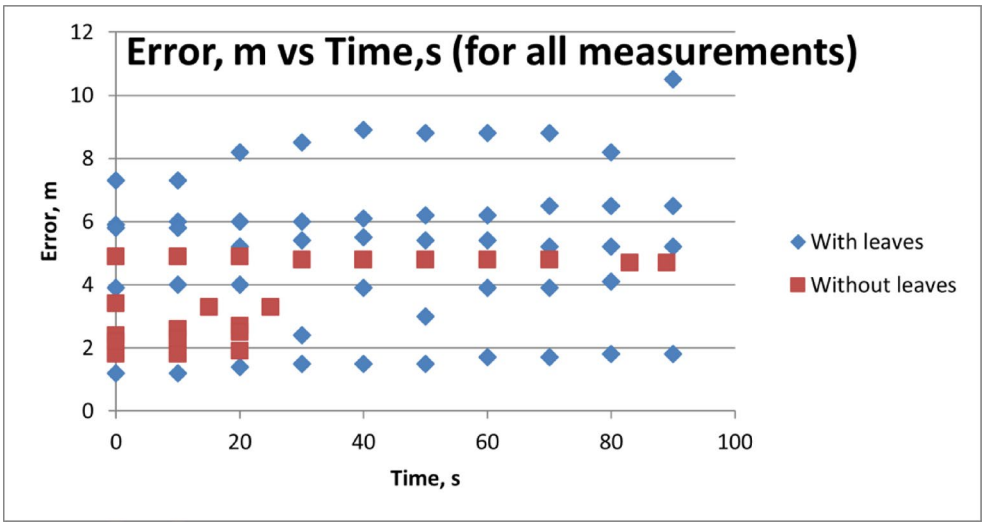


Fig. 3. Variation of positioning errors during the measurement period for conditions with and without foliage.

Position number	1	2	3	4	5
With leaves, m	1.53	6.19	5.43	3.68	8.53
Without leaves, m	4.81	3.33	2.57	1.83	2.33

Table 2. Average positioning errors at each measurement position under foliage and non-foliage conditions.

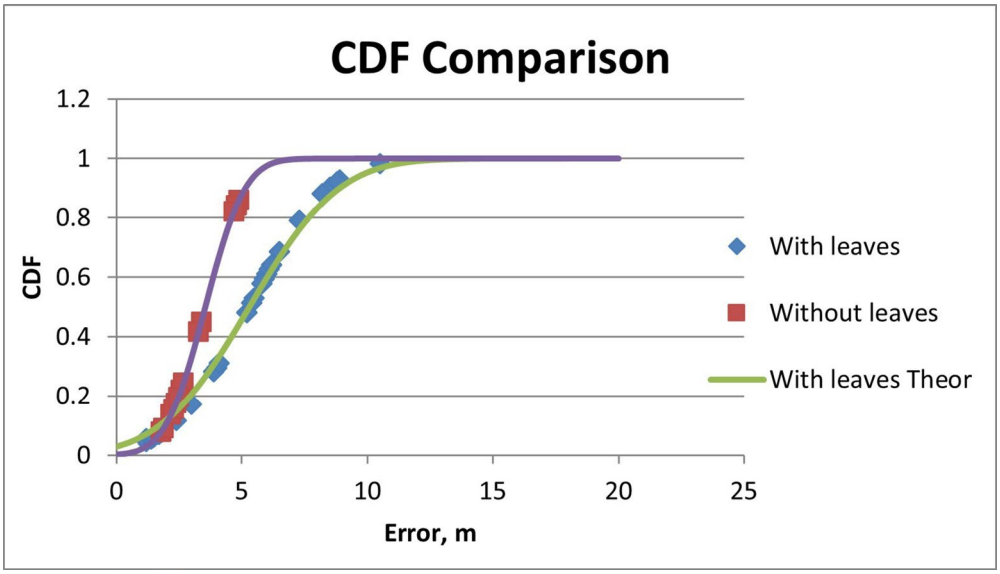


Fig. 4. Comparison of cumulative distribution functions (CDF) of positioning errors under foliage and non-foliage conditions. Solid lines represent the corresponding theoretical Gaussian distributions.

A comparison of the obtained variances additionally showed that measurements performed without foliage were generally more stable. In most cases, the variance values obtained without foliage were between 2 and 30 times lower than those measured in the presence of foliage.

This tendency is also confirmed by the comparison of the average variance values across all measurement positions. In the presence of foliage, the average variance reached 5.99 m^2, whereas in the absence of foliage it decreased to 1.54 m^2. Similar differences can also be observed in the cumulative distribution functions shown in Fig. 4. The obtained error distributions can be reasonably approximated by a Gaussian distribution.

Table 3 summarizes several additional parameters describing GPS localization accuracy under both experimental conditions.

	With leaves	Without leaves
Median	5.4	3.35
9th Decile	8.8	4.88
R95	11.23	6.97
DRMS (m)	0.055457	4.04E–05
C/N Mean (all SAT)	31.41037	33.05
C/N Mean (4 SAT)	37.02	40.22
Variance	5.99	1.54
Skewness	0.618182	− 0.12334

Table 3. Comparison of GPS positioning accuracy parameters under foliage and non-foliage conditions.

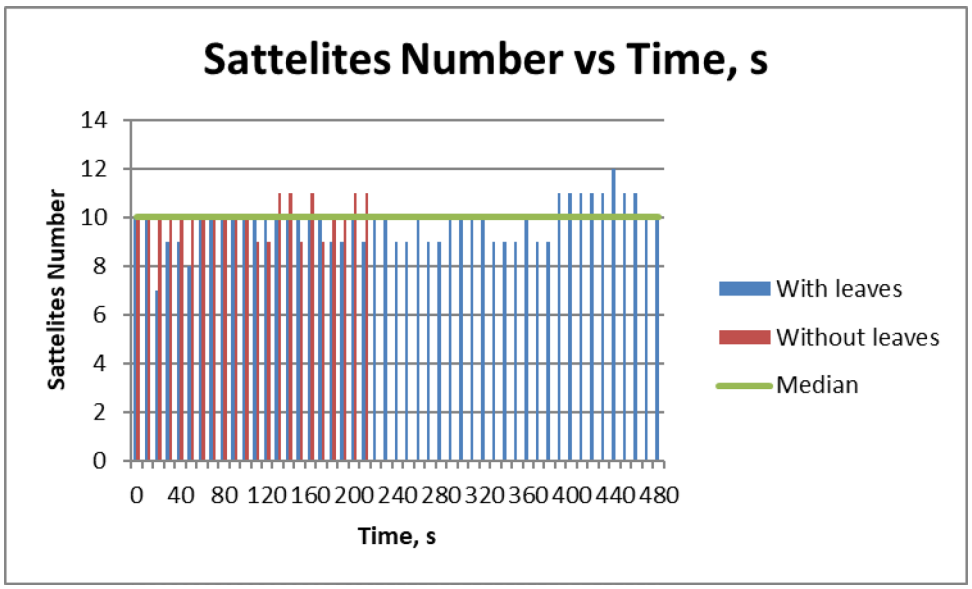


Fig. 5. Variation in the number of visible satellites during measurements with and without foliage.

The calculated skewness coefficients indicate that the positioning errors obtained without foliage were relatively symmetrical, suggesting a smaller dispersion of the measured results. In contrast, the skewness coefficient obtained in the presence of foliage exceeded 0.5, indicating a moderate asymmetry in the error distribution.

Excess kurtosis was also evaluated in order to characterize the shape of the obtained distributions. Under foliage conditions, the kurtosis coefficient was slightly greater than 1, indicating a leptokurtic distribution with a higher probability of larger deviations from the mean value. This suggests that occasional larger positioning errors may occur in dense canopy conditions. In contrast, the kurtosis coefficient obtained without foliage was below 1, indicating a more uniform distribution of positioning errors and generally more stable localization results.

Figure 5 presents the variation in the number of visible satellites during the measurement period. The obtained results indicate that foliage had only a minor influence on the number of observed GPS satellites. Despite the approximately two-month interval between the two measurement campaigns, the median number of visible satellites remained identical in both experimental cases. This suggests that satellite visibility conditions were generally similar during the measurements with and without foliage.

The influence of foliage on the carrier-to-noise ratio (C/N) was also investigated. Two separate analyses were performed. In the first case, the variation of the four strongest satellite signals was evaluated, since at least four satellites are required for reliable three-dimensional positioning. In the second case, the C/N variation of all visible satellites was analysed in order to evaluate the overall signal reception conditions. The corresponding results are presented in Figs. 6 and 7.

The results shown in Fig. 6 demonstrate that measurements performed without foliage generally produced higher C/N values than measurements obtained under foliage conditions. In most cases, the C/N values without foliage were close to or exceeded 40 dB-Hz, which is typically considered a strong and reliable GNSS signal. In contrast, under foliage conditions, the majority of C/N values ranged between approximately 33 and 39 dB-Hz, indicating weaker signal reception conditions.

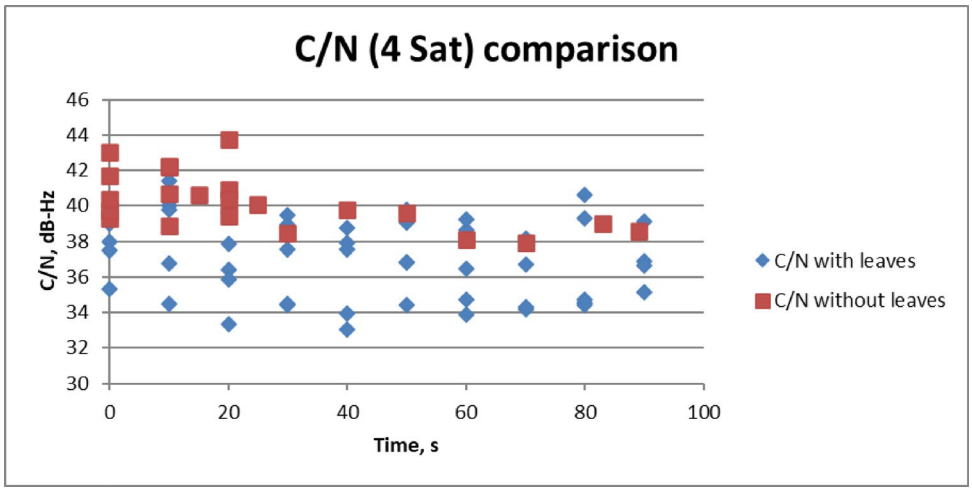


Fig. 6. Variation of the carrier-to-noise ratio (C/N) for the four strongest satellite signals under foliage and non-foliage conditions.

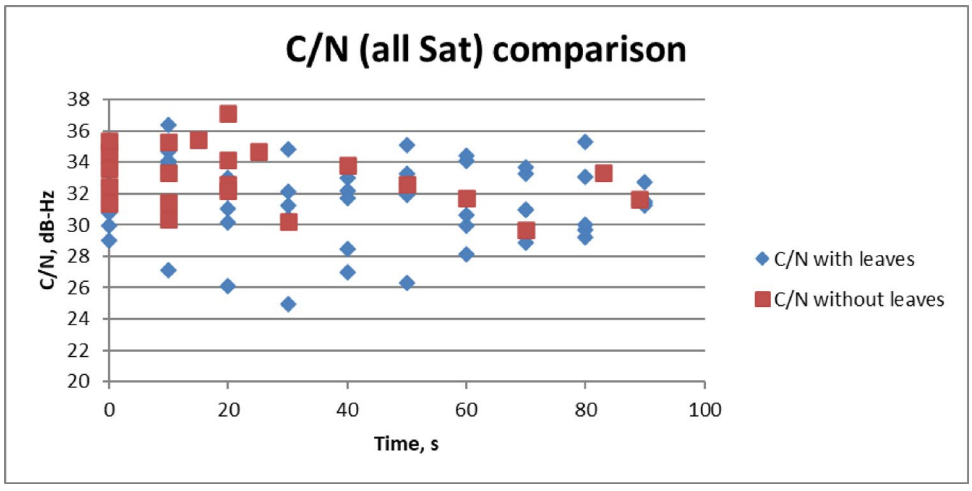


Fig. 7. Variation of the carrier-to-noise ratio (C/N) for all visible satellites under foliage and non-foliage conditions.

A similar tendency was observed when analysing the C/N variation of all visible satellites. The overall distribution and variation of the C/N values remained consistent with the results obtained from the four strongest satellite signals, confirming the negative influence of foliage on GNSS signal quality.

The difference between measurements with and without foliage becomes even more evident when analysing the C/N values of all visible satellites. In the absence of foliage, most C/N values ranged between approximately 30 and 38 dB-Hz, which corresponds to generally acceptable GNSS signal quality. Under foliage conditions, however, a considerable number of C/N values fell below 30 dB-Hz. Such signal levels are typically considered weak and may reduce the reliability of positioning results.

PDOP, HDOP, and VDOP parameters also have an important influence on localization accuracy. The corresponding PDOP/HDOP and VDOP/HDOP ratios are presented in Fig. 8. Throughout all experiments, the recorded PDOP, HDOP, and VDOP values remained very good regardless of foliage conditions. PDOP values varied between approximately 0.9 and 1.2, HDOP between 0.6 and 1.0, and VDOP between 0.7 and 0.8.

As expected, the PDOP/HDOP ratio remained greater than 1 during most measurements. This is consistent with typical GNSS positioning conditions, where vertical positioning errors usually contribute more strongly to the overall positioning uncertainty than horizontal errors due to satellite geometry limitations.

The VDOP/HDOP ratio obtained under foliage conditions was also greater than 1 in most cases, indicating lower vertical positioning accuracy. In contrast, during measurements without foliage, this ratio was often close to unity, suggesting particularly favorable satellite geometry during the observation period. In several cases, the VDOP/HDOP ratio was observed to be slightly below 1 both with and without foliage. Although such situations are relatively uncommon, they may occur under specific satellite arrangements and favorable observation geometry.

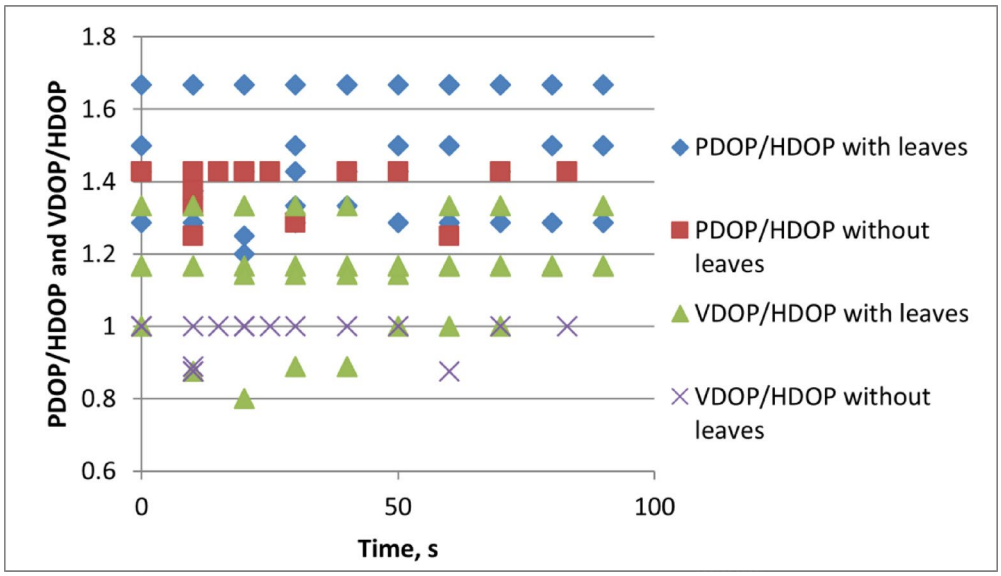


Fig. 8. Variation of PDOP/HDOP and VDOP/HDOP ratios under foliage and non-foliage conditions.

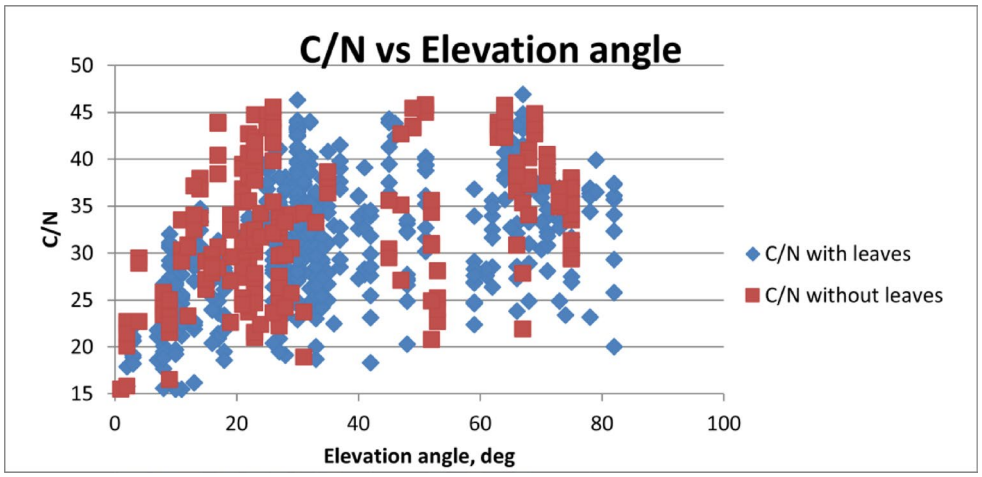


Fig. 9. Dependence of the carrier-to-noise ratio (C/N) on satellite elevation angle.

Figure 9 presents the variation of the C/N ratio as a function of satellite elevation angle. Most visible satellites were observed at elevation angles between approximately 10° and 40°, as well as between 60° and 75°. Several local C/N maxima can also be distinguished, particularly near elevation angles of 25–30°, around 50°, and close to 70°. At very low and very high elevation angles, especially below approximately 15° and above 75°, the C/N ratio decreased noticeably, which may additionally contribute to reduced localization accuracy.

Several limitations of this study should be acknowledged. First, the experiments were performed using a single smartphone-based GNSS receiver and within a single urban park environment. Therefore, the obtained results may not fully represent GNSS performance under different environmental or hardware conditions.

Second, the reference coordinates were obtained from Google Maps rather than from survey-grade geodetic measurements. Although this limits the evaluation of absolute positioning accuracy, the same reference framework was consistently applied throughout all experiments, allowing reliable comparative analysis between foliage and non-foliage conditions.

In addition, the number of measurements performed without foliage was smaller than the number of measurements obtained during foliage conditions because the first measurement campaign demonstrated that three repeated observations were sufficient to obtain stable coordinate estimates. Therefore, the reduced number of repetitions is not expected to have materially influenced the comparison between foliage and non-foliage conditions.

Future studies should include larger datasets, multiple GNSS receiver types, additional vegetation environments, and high-precision reference positioning systems in order to further validate and generalize the obtained results.

Conclusions

This study investigated the influence of tree canopy and foliage on GPS positioning accuracy in a vegetation-rich park environment using a smartphone-based GNSS receiver. The obtained results indicate that foliage may significantly affect localization accuracy and GNSS signal quality under the investigated experimental conditions. The performed measurements showed that positioning errors under foliage conditions were generally higher than those obtained without foliage. Depending on the measurement location, positioning errors increased by approximately 1.86 to 3.66 times in the presence of foliage. However, several exceptional cases were also observed, suggesting that local environmental conditions and multipath propagation effects may additionally influence localization performance.

Statistical analysis demonstrated that measurements performed without foliage generally produced lower variance, smaller error dispersion, and more stable positioning results. Parameters such as CEP, R95, DRMS, and 9th decile values also indicated improved localization reliability in the absence of foliage.

The obtained results further showed that foliage had a stronger influence on GNSS signal quality than on the number of visible satellites. Although the number of observed satellites remained relatively similar in both experimental scenarios, carrier-to-noise ratio (C/N) values were noticeably lower under foliage conditions. In several cases, C/N values below 30 dB-Hz were observed in dense canopy conditions, indicating degraded signal reception quality and reduced positioning reliability.

The recorded PDOP, HDOP, and VDOP values remained favorable throughout the experiments, suggesting that satellite geometry conditions were generally suitable for reliable positioning analysis. Consequently, the observed differences in localization accuracy can primarily be associated with foliage-related signal attenuation and multipath effects.

The obtained results contribute to a better understanding of GNSS positioning performance in vegetation-rich environments and may be useful for the development of outdoor navigation and assistive mobility systems operating under complex environmental conditions.

Future research should include experiments using additional GNSS constellations, survey-grade reference positioning systems, larger datasets, and different environmental conditions in order to further improve localization error prediction and mitigation methods.

Data availability

The datasets generated and/or analysed during the current study are available from the corresponding author upon reasonable request.

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Declarations

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