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GNSS Positioning Accuracy in Forest Environments: A Structured Critical Review of Canopy Effects and Mitigation Strategies

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ABSTRACT. GNSS positioning under forest canopy remains challenging, as vegetation attenuates signals, promotes multipath propagation, and degrades satellite geometry. This paper presents a structured critical narrative review of the scientific literature published between 1996 and 2025, updated through a search to 2026. Autonomous GNSS, DGPS, RTK-GNSS, multi-GNSS and low-cost RTK, as well as GNSS–IMU, LiDAR, UAV, UWB, and SLAM approaches are compared. Evidence indicates a progressive deterioration in performance with canopy density. In the reviewed studies, autonomous GNSS errors frequently reach 15–30 m under dense canopy, while multi-GNSS RTK solutions report, under comparable conditions, approximately 0.5–2.03 m; ranges are indicative, not statistically aggregated estimates. GNSS integration with inertial sensors and LiDAR increases continuity and robustness, but operational validation remains limited. The main contribution is a decision-oriented framework that correlates canopy, degradation mechanisms, technology and mitigation strategies. Three priorities are highlighted: standardized reporting, forest-adapted corrections and comparative validation of multi-sensor systems.

Keywords: GNSS, forest canopy, positioning accuracy, RTK, LiDAR.

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1. Introduction

Global Navigation Satellite Systems (GNSS) have become indispensable tools for forest surveys, supporting applications such as forest inventories, management planning, road mapping, precision forestry, and georeferencing airborne and ground-based remote sensing data (White et al. 2016, Liang et al. 2016, Wulder et al. 2008). Continued advances in multi-frequency and multi-constellation receivers have greatly improved positioning performance in open environments, enabling centimeter-level accuracy for many survey applications (Hofmann-Wellenhof et al. 2008, Kaplan and Hegarty 2017). However, forest environments remain among the most challenging operational conditions for GNSS positioning, as tree canopy alters signal propagation through attenuation, multipath propagation, reduced satellite visibility, and degraded satellite geometry.

Numerous experimental studies have investigated the influence of forest canopy on GNSS positioning. Early research established the fundamental effects of canopy structure and terrain on positioning accuracy (Deckert and Bolstad 1996, Sigrist et al. 1999), while later studies evaluated differential positioning techniques, Real-Time Kinematic (RTK) solutions, multi-constellation receivers, and more recently, low-cost GNSS platforms and multi-sensor systems (Bolstad et al. 2005, Pirti et al. 2010, Tomaštík and Everett 2023, Cățeanu and Moroianu 2024). Parallel advances in the integration of GNSS with inertial measurement units (IMUs), light detection and ranging (LiDAR), unmanned aerial vehicles (UAVs), and simultaneous localization and mapping (SLAM) solutions have further expanded the range of positioning solutions available for forestry applications. General reviews of forest remote sensing have examined the role of LiDAR and other sensors in forest inventory but have not systematically compared GNSS accuracy across technology classes and canopy conditions (White et al. 2016, Wulder et al. 2008).

Although these studies have substantially advanced the understanding of GNSS performance under the forest canopy, the available evidence remains fragmented. Different studies focus on individual technologies, adopt heterogeneous experimental protocols, use different canopy descriptors, and report positioning accuracy using incomparable metrics. Therefore, practitioners and researchers still lack an integrated framework that allows for the comparison of positioning technologies in contrasting forest conditions and supports the selection of the most appropriate solution for specific operational requirements.

The objective of this review is not simply to summarize previous studies, but to critically integrate nearly three decades of experimental evidence into a unified comparative framework. Specifically, the review addresses three questions: (1) How do canopy characteristics and terrain conditions influence GNSS positioning performance? (2) How does the positioning performance—in terms of accuracy and operational reliability—compare across autonomous GNSS, DGPS, RTK, multi-constellation RTK, and integrated multi-sensor solutions under varying forest canopy and terrain conditions? (3) What methodological limitations currently hinder comparison between studies and operational implementation?

The reviews identified through the search strategy did not simultaneously integrate these dimensions into a single decision-oriented framework. The main contributions of the paper are: (*i*) the structured comparison of two families of approaches—GNSS technologies and complementary technologies; (*ii*) a synthesis framework for technology selection under contrasting canopy conditions; and (*iii*) identification of methodological priorities for standardized reporting, forest environment-adapted corrections, and multi-sensor validation.

To answer these questions, the review systematically compares two families of approaches: (A) GNSS technologies and (B) complementary technologies. The analysis correlates canopy conditions, signal degradation mechanisms, positioning performance, operational constraints, and mitigation strategies. The resulting synthesis supports technology selection based on environmental conditions and required accuracy and highlights methodological priorities for future research.

Rather than identifying a universally superior positioning technology, this review indicates that optimal GNSS solutions depend on the interaction between canopy structure, terrain characteristics, required accuracy, operational constraints, and available resources. The positioning of this review in relation to the previous literature is summarized in Table 1. The table systematically compares previous studies according to four dimensions: the technologies covered, the forest and geographic context, whether a cross-technology comparison was performed, and whether a gap analysis was conducted. This structured comparison shows that the reviewed literature generally addresses individual technologies or restricted forest contexts, whereas the present review integrates the principal GNSS technology classes and complementary sensor families into a unified decision-oriented framework applicable to contrasting forest conditions.

Table 1. *Positioning of this review in relation to previous literature.*

Study	Technology covered	Forest / geographic context	Cross-technology comparison?	Gap analysis?
Pirti (2008)	Autonomous GPS	Turkish forests — near boundary	No	No
Næsset and Jonmeister (2002)	DGPS only	Scandinavian forests	No	No
Pirti et al. (2010)	RTK GPS + GLONASS	Under/near canopy, Turkey	No — 2 constellations	No
Wing et al. (2005)	Consumer-grade GPS	Pacific Northwest, USA	No	No
Feng et al. (2021)	Single-point GNSS	Conifers & broadleaves, China	No	Partial
Bolstad et al. (2005)	Autonomous, WAAS, RTK, post-processing	Northern forests, USA	Partial — 4 GPS variants	No
Tomaštík and Everett (2023)	Low-cost RTK (ZED-F9P)	Under canopy, Slovakia	No	No
Abdi et al. (2022)	Low-cost RTK + LiDAR	Logging trails, Finland	No	No
Cățeanu and Moroianu (2024)	Survey-grade multi-GNSS RTK	Romanian forests	No	No
Faitli et al. (2023)	Inertial LiDAR + SLAM	Forestry automation, Finland	No	No
Proudman et al. (2022)	Handheld LiDAR + SLAM	Forest inventory, UK	No	No
White et al. (2016)	Remote sensing (general review)	Global — not GNSS-specific	No	Partial
Wulder et al. (2008)	LiDAR in forest management	Global — not a GNSS review	No	No
THIS REVIEW (1996–2025, updated 2026)	(A) GNSS technologies: autonomous, DGPS, RTK, networked RTK, multi-GNSS, PPP/PPP-AR, survey-grade or low-cost receivers; (B) complementary technologies: GNSS–IMU, inertial LiDAR, SLAM, UWB and UAV	Nearly three decades; forest contexts from Europe, North America, and East Asia	Yes — two families in a unified framework	Yes — three gaps

2. Materials and Methods

This paper is a structured critical narrative review, intended to provide a comparative synthesis of results on GNSS accuracy in forest environments (Feng et al. 2021, Pirti 2008).

The narrative design was chosen because studies differ in equipment, correction methods, terrain and error indicators, which does not allow for a valid meta-analysis (Feng et al. 2021, Wing et al. 2005, Page et al. 2021). The search covered Web of Science, Scopus, and Google Scholar for the period 1996–2025 and was updated with publications available online up to 2026.

The strategy combined the terms forest/canopy with GNSS/GPS, accuracy/positioning/error and the descriptors RTK, DGPS, IMU/INS (Inertial Measurement Unit/Inertial Navigation System), LiDAR, UAV, UWB (Ultra-Wideband) and SLAM. The main strings were:

- Web of Science:

(GNSS OR GPS) AND (forest* OR canopy) AND (accuracy OR positioning OR error)

- Scopus:

TITLE-ABS-KEY((GNSS OR GPS) AND (forest OR canopy) AND (accuracy OR RTK OR DGPS))

- Google Scholar:

"GNSS positioning" "forest canopy" accuracy.

For complementary technologies, targeted searches were performed with:
(IMU OR INS OR LiDAR OR UAV OR UWB OR SLAM) AND (forest* OR canopy) AND (positioning OR localization OR georeferencing OR accuracy).

The last search was performed in July 2026.

Only scientific publications with verifiable bibliographic information were retained for Google Scholar. The criteria applied to the main body of empirical evidence were: forest environment or explicit analysis of the canopy effect; quantitative indicators of accuracy; evaluation of a relevant technology for positioning or georeferencing; and publication in a verifiable scientific source. Open-field studies only, papers without quantitative indicators, unpublished technical reports, and sources without direct relevance were excluded. The selection flow, adapted to a critical narrative review and inspired by PRISMA (Page et al. 2021), identified 306 records. After eliminating 90 duplicates, 216 titles and abstracts were analyzed. Following the evaluation of titles and abstracts, 115 records were excluded, and 101 full texts were assessed for eligibility. After excluding 27 full texts, 74 sources were included in the critical synthesis. Of these, 51 are cited directly in the manuscript and appear in the reference list, as required by the journal; the full bibliography and mapping of the 74 sources are presented in Appendix A. Empirical studies with quantitative indicators constituted the main body of evidence; methodological volumes, syntheses and general papers were used only for conceptual substantiation and were not treated as equivalent in deriving error ranges.

For each included empirical study, the following were systematically extracted: geographical region, forest type, canopy metric used, terrain condition, receiver or sensor class, correction method, observation duration, accuracy indicator, reported error range, main limitation and proposed mitigation strategy.

These were grouped thematically by technology analyzed (Pirti 2008, Feng et al. 2021), canopy conditions (Sigrist et al. 1999, Bolstad et al. 2005), accuracy indicators and relevance to forestry applications. The synthesis follows degradation mechanisms (Deckert and Bolstad 1996), performance as a function of canopy density (Pirti et al. 2010, Næsset and Jonmeister 2002), contribution of complementary sensors (Groves 2013, Faitli et al. 2023), and methodological gaps (Page et al. 2021, Wing et al. 2005).

The process of identification, initial selection, eligibility assessment, and inclusion of sources is summarized in Figure 1.

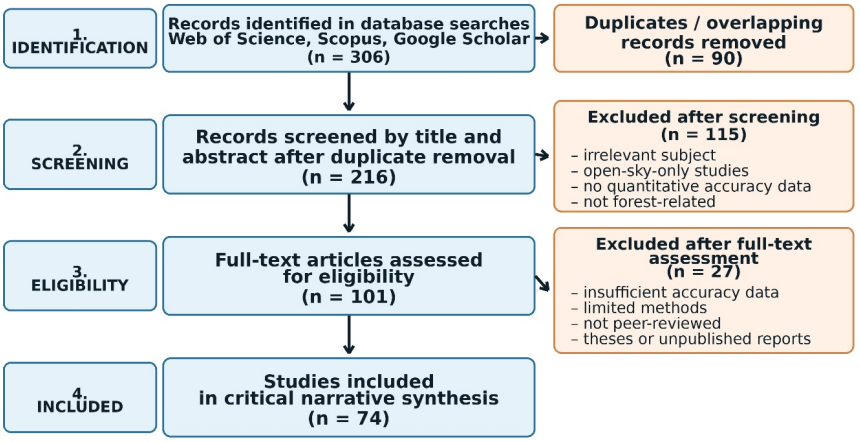

Figure 1. *Literature selection flow, inspired by the PRISMA methodology. Source: own elaboration based on PRISMA principles (Page et al. 2021).*

3. Results and Discussion

3.1. GNSS Fundamentals and Challenges in Forest Environments

GNSS accuracy depends on the geometry of the visible satellites (DOP), signal quality, and receiver type (Hofmann-Wellenhof et al. 2008, Kaplan and Hegarty 2017), factors that are directly affected by the forest canopy. In forests, the signal is degraded by attenuation, multipath propagation, and reduced satellite visibility, which increases the DOP and reduces accuracy. Conifers produce relatively constant obstruction, while broadleaves have seasonal variability (Pirti 2008, Sigrist et al. 1999). Relief amplifies these effects in hilly and mountainous areas (Deckert and Bolstad 1996, Magiera et al. 2022, Konakoglu and Yilmaz 2024).

Figure 2 summarizes the conceptual relationship between canopy and GNSS accuracy: as canopy density increases, the signal weakens, the probability of multipath propagation increases, DOP degrades, and positioning error increases (Feng et al. 2021, Sigrist et al. 1999, Bolstad et al. 2005). The value below 0.1 m illustrated for open terrain refers to RTK/multi-GNSS solutions under favorable conditions, not to autonomous GNSS positioning. Taken together, results obtained in coniferous (Feng et al. 2021), deciduous (Pirti 2008), boreal (Faitli et al. 2023), and mixed alpine forests (Hollaus et al. 2006, Magiera et al. 2022) support the same general chain of degradation. The figure therefore represents a qualitative conceptual framework and not a universal quantitative model.

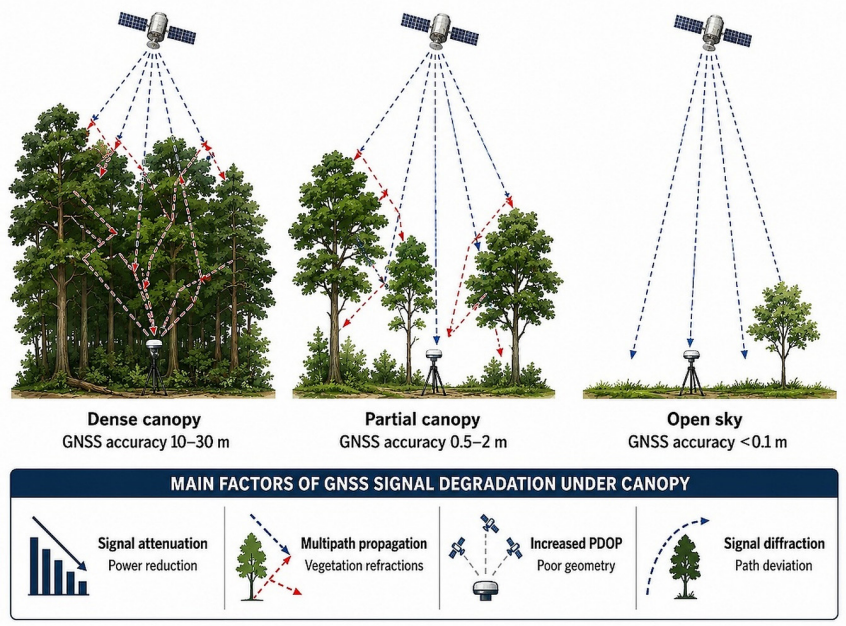

Figure 2. *Conceptual relationship between forest canopy characteristics and GNSS positioning accuracy. Source: Own elaboration based on the analyzed literature (Sigrist et al. 1999, Deckert and Bolstad 1996, Pirti et al. 2010, Căţeanu and Moroianu 2024, Tomaštík and Everett 2023, Groves 2013, Faitli et al. 2023, Proudman et al. 2022).*

3.2. GNSS Technologies for Forestry Applications

For the analysis, the approaches were organized into two families: (A) GNSS technologies—autonomous positioning, DGPS, RTK, networked RTK, multi-GNSS, PPP/PPP-AR (Precise Point Positioning/Precise Point Positioning with Ambiguity Resolution), and low-cost or survey-grade receivers; and (B) complementary technologies—GNSS–IMU, inertial LiDAR, SLAM, UWB, and UAV.

Autonomous GNSS receivers are affordable, but errors can reach 10–30 m under dense canopy (Wing et al. 2005, Pirti 2008, Sigrist et al. 1999). DGPS reduces errors to the metric level but remains sensitive to attenuation and multipath propagation (Næsset and Jonmeister 2002, Bolstad et al. 2005). RTK-GNSS provides centimeter accuracy in open fields, but below canopy can lose the fixed solution and switch to a floating solution, with errors of 1–3 m (Pirti et al. 2010, Ogundipe et al. 2014). Multi-GNSS RTK increases satellite availability and can limit errors to approximately 0.5–2.03 m under dense canopy (Cățeanu and Moroianu 2024, Tomaštík & Everett 2023). In dense coniferous forests in the northwestern United States, topographic-class receivers used with postprocessing have achieved horizontal errors below 1–2 m, with performance depending on observation duration, antenna height, and distance from the reference station (Strunk et al. 2025).

Several reviewed studies indicate a marked deterioration in positioning performance at high canopy closure, with significant degradation frequently reported at values of about 70–80% or higher. A recent study confirmed that performance differences between forest environments with varying vegetation density are statistically significant (Rybansky et al. 2026). However, this range should not be treated as a universal operational threshold, as canopy closure was measured and classified differently between studies, and receptor class, season, terrain, and observation protocol also influence the resulting accuracy (Feng et al. 2021, Groves 2013, Faitli et al. 2023). Indicative error ranges are summarized in Table 2 and Table 3.

Table 2. *Indicative error ranges reported for GNSS technologies depending on canopy conditions.*

GNSS Technology	Open / low	Partial (30–70%)	Dense (>70%)	Robustness	Key references
Autonomous GNSS	5–10 m	10–20 m	15–30 m	Low	Sigrist et al. (1999), Wing et al. (2005), Pirti (2008), Feng et al. (2021)
DGPS	1–3 m	3–6 m	5–8 m	Low–moderate	Næsset and Jonmeister (2002), Bolstad et al. (2005)
RTK GPS/ GLONASS	Centimeter-level	0.2–1 m	1–3 m; frequently fixed→ floating	Moderate	Pirti et al. (2010), Ogundipe et al. (2014), Pirti and Yucel (2022)
Multi-GNSS RTK	Centimeter-level	0.05–0.3 m	0.5–2.03 m	High	Cățeanu and Moroianu (2024), Tomaštík and Everett (2023)
Low-cost RTK (ZED-F9P)	<0.1 m	<0.1 m	0.3–1.5 m	Moderate–high	Tomaštík and Everett (2023), Abdi et al. (2022), Magiera et al. (2022), Konakoglu and Yilmaz (2024)

In the decision-oriented synthesis, conditions were operationally grouped as: open field or low canopy (<30%), partial canopy (30–70%), and dense canopy (>70%). The ranges are indicative. The categories multi-GNSS RTK and low-cost RTK describe partially overlapping dimensions—number of constellations and cost class, respectively—and are separated only for operational comparison, not as mutually exclusive technologies.

Table 3. *Methodological context and comparability of the analyzed approaches.*

Type	Approach	Range	Metric	Solution	Duration / equipment	No., key sources
A	Autonomous GNSS	10–30 m	H error	Static or kinematic; single point	Seconds–minutes; consumer or mapping-grade receiver	5, Sigrist et al. (1999), Wing et al. (2005), Pirti (2008), Feng et al. (2021)
	DGPS	3–8 m	H error	Static or kinematic; differential (WAAS/SBAS)	Minutes–hours; mapping-grade receiver	3, Næsset and Jonmeister (2002), Bolstad et al. (2005)
	RTK-GNSS	0.2–3 m	2D RMSE; H+V	Kinematic; fixed or floating solution	Seconds–minutes; survey-grade receiver	3, Pirti et al. (2010), Ogundipe et al. (2014), Pirti and Yucel (2022)
	Multi-GNSS RTK	0.05–2.03 m	2D RMSE; H+V	Kinematic; fixed or floating solution	Seconds–minutes; survey-grade receiver	3, Cățeanu and Moroianu (2024), Tomaštík and Everett (2023)
	Low-cost RTK	<0.1–1.5 m	H RMSE	Static; fixed or floating solution	5–30 min; u-blox ZED-F9P	4, Tomaštík and Everett (2023), Abdi et al. (2022), Magiera et al. (2022), Konakoglu and Yilmaz (2024)
B	GNSS–IMU / Inertial LiDAR	≈0.1–1 m	3D error	GNSS–IMU integration	Continuous; survey-grade GNSS + IMU	4, Groves (2013), Faitli et al. (2023), Noureldin et al. (2013), Proudman et al. (2022)
	UWB	0.1–0.5 m	H/3D error	Local; no GNSS	Continuous; UWB tag + fixed anchors	1, Liu et al. (2025)
	Mobile LiDAR / SLAM	0.1–0.5 m local; drift over long paths	3D error	SLAM; no GNSS	Continuous; LiDAR + INS	2, Muhojoki et al. (2024), Faitli et al. (2023)

Note: The ranges are indicative, come from studies with different receivers, indicators and protocols and do not represent statistically aggregated estimates. Panel A compares only GNSS technologies for which crown conditions are reported in a relatively comparable form. Panel B presents the methodological context and separates complementary technologies; UWB and LiDAR / SLAM values should not be interpreted as directly equivalent to GNSS errors. Robustness is a qualitative assessment derived from the literature reviewed.

Table 4 presents the decision-oriented synthesis framework. The matrix was constructed by systematically correlating each crown condition with the dominant degradation mechanism identified in the reviewed literature (Sigrist et al. 1999, Feng et al. 2021, Deckert and Bolstad 1996), with the best-performing technology documented in that condition (Pirti et al. 2010, Tomaštík and Everett 2023, Cățeanu and Moroianu 2024, Groves 2013), and with the mitigation strategies with empirical support in the reviewed literature (Faitli et al. 2023, Proudman et al. 2022). This matrix represents its own synthesis built based on the reviewed literature and constitutes one of the main contributions of the review.

Table 4. *Decision-oriented synthesis framework for GNSS positioning under forest canopy.*

Condition	Mechanism	Approach	Limitation	Mitigation	Key references
Open field / low canopy	Minimal obstruction; favorable geometry	RTK-GNSS / Multi-GNSS RTK	Cost and complexity	Standard RTK or PPK	Pirti et al. (2010), Cățeanu and Moroianu (2024)
Partial canopy (30–70%)	Moderate attenuation; multipath propagation	Multi-GNSS RTK / Low-cost RTK	Variable stability	Longer observations; satellite window planning	Tomaštík and Everett (2023), Abdi et al. (2022)
Dense canopy (>70%)	Strong attenuation; high DOP	GNSS–IMU / LiDAR / SLAM	Drift; cost; validation	Sensor fusion; control points	Faitli et al. (2023), Proudman et al. (2022)
Rugged terrain	Canopy and topographic obstruction	Integrated GNSS–IMU–LiDAR system	Difficult implementation	Terrain-adapted survey planning	Groves (2013), Faitli et al. (2023)

Source: Own elaboration based on the analyzed literature (Sigrist et al. 1999, Deckert and Bolstad 1996, Pirti et al. 2010, Cățeanu and Moroianu 2024, Tomaštík and Everett 2023, Groves 2013, Faitli et al. 2023, Proudman et al. 2022).

3.3. Integration With Inertial Measurement Units (IMU), LiDAR and UAVs

In dense canopy conditions, GNSS positioning can become unstable for applications requiring high accuracy. The integration of GNSS with complementary sensors is thus one of the major directions for improving forest positioning.

Integrated solutions include IMU, LiDAR, UAV and SLAM. GNSS–IMU maintains positioning continuity when the signal is degraded or interrupted (Groves 2013, El-Sheimy et al. 2008, Noureldin et al. 2013): IMU estimates motion through accelerations and rotations, and GNSS corrects for inertial drift. LiDAR provides 3D information about terrain, trees and canopy (Andersen et al. 2006, Reutebuch et al. 2003). In UAV–LiDAR applications, GNSS positioning errors affect point-cloud georeferencing and may consequently influence the derived digital terrain model (DTM), tree-height estimates, and forest inventory metrics (Næsset 2004, Wallace et al. 2012, Puliti et al. 2020),

while terrestrial or mobile LiDAR reduces GNSS dependence but can accumulate trajectory errors. A systematic comparison of mobile canopy laser scanning systems has revealed significant differences in accuracy between platforms (Muhojoki et al. 2024). In dense forests, the placement of control points and GNSS reception are difficult, limiting the final accuracy (Puliti et al. 2020, Wallace et al. 2012).

LiDAR-based SLAM methods can maintain location when GNSS is degraded, but over long paths they accumulate drift (Proudman et al. 2022, Faitli et al. 2023). UWB and cooperative INS–GNSS systems offer alternatives for personnel tracking and rescue operations (Liu et al. 2025, Ji et al. 2025). For roads and inventories, the usefulness of the solutions depends on the equipment class and georeferencing (Bettinger and Merry 2012, Liang et al. 2016). Mobile or airborne laser scanning and UAV photogrammetry can improve tree and canopy mapping, but accuracy remains tied to control points and reference positioning (Beniušienė et al. 2026, Dandois and Ellis 2013, Lisein et al. 2013, Dubayah and Drake 2000, Næsset et al. 2004, Breidenbach et al. 2010, Beland et al. 2019). Evaluations for smartphones, laser scanners, and receivers of different classes confirm important variations between platforms and modes of operation (Tomaštík et al. 2017, Vastaranta et al. 2013, Holopainen et al. 2010, Wing et al. 2007, Wing and Kellogg 2004, Kaartinen et al. 2015).

Figure 3 qualitatively summarizes the expected robustness as canopy density increases. The curves and vertical axis levels are conceptual, not statistically aggregated quantitative estimates.

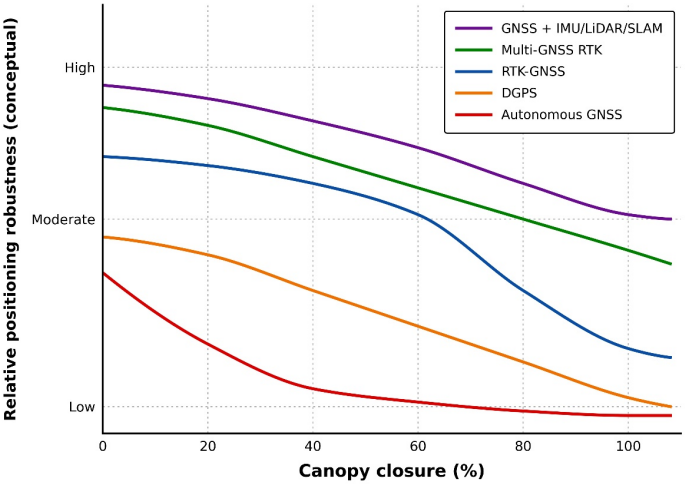

Figure 3. *Conceptual comparison of the expected relative robustness of positioning technologies as a function of canopy density. The curves indicate qualitative trends and do not represent statistically aggregated quantitative estimates. Source: Own elaboration based on the works Sigrist et al. (1999), Pirti et al. (2010), Abdi et al. (2022), Tomaštík and Everett (2023), Cățeanu and Moroianu (2024), Groves (2013), Faitli et al. (2023), and Proudman et al. (2022).*

3.4. Factors Affecting the Accuracy of GNSS Positioning in Forest Environments

GNSS accuracy in forests results from the interaction of several factors. Several studies report a sharp deterioration in conditions of high canopy closure, often around or above the range of 70–80%; however, this range should not be interpreted as a universal threshold, as canopy metrics, receptor class, season, terrain, and observation protocols differ between studies (Feng et al. 2021, Pirti et al. 2010, Bolstad et al. 2005, White et al. 2016). Conifers produce relatively constant obstruction, and broadleaves are more favorable in vegetative dormancy (Deckert and Bolstad 1996, Pirti 2008, Sigrist et al. 1999). Topography amplifies the effects through steep slopes and narrow valleys (Magiera et al. 2022, Konakoglu and Yilmaz 2024, Wing et al. 2005). Vegetation density significantly influences the accuracy of GNSS navigation for land-based logging vehicles (Rybansky et al. 2026). Multi-frequency and multi-constellation receivers are more likely to maintain the solution below the canopy, although the advantage decreases at high density (Næsset and Jonmeister 2002, Pirti et al. 2010, Abdi et al. 2022, Cățeanu and Moroianu 2024). Longer observations and RTK improve accuracy only if the signal allows a fixed solution to be obtained (Pirti et al. 2010, Ogundipe et al. 2014, Pirti and Yucel 2022).

A structural limitation identified by the literature review is the lack of a common reporting protocol: studies differ in receiver type, constellations used, observation duration, correction method, canopy description, and error indicator, making direct comparison difficult (Feng et al. 2021, Wing et al. 2005, Page et al. 2021). The synthesis framework in Table 4 directly addresses this gap.

GNSS technologies are used in forestry for locating sample plots, delimiting management units, mapping forest roads, and georeferencing LiDAR/UAV data (White et al. 2016, Puliti et al. 2020, Wulder et al. 2008). The choice of technology must be correlated with the required accuracy and field conditions: stand-alone GNSS is sufficient for general orientation (Wing et al. 2005, Pirti 2008), multi-GNSS RTK is suitable in sparse or partially covered forests (Tomaštík and Everett 2023, Abdi et al. 2022), and GNSS–IMU, LiDAR or SLAM solutions become necessary in dense forests, with trade-offs in cost and complexity (Groves 2013, Faitli et al. 2023, Proudman et al. 2022). A major problem is the lack of methodological standardization: studies differ in receiver, duration, accuracy indicators and description of forest conditions (Feng et al. 2021, Pirti 2008, Wing et al. 2005, Page et al. 2021). Future studies should systematically report receiver type, constellations, duration, correction method, canopy density, vegetation, relief, and reference position. The lack of forest-adapted correction models remains a critical gap, and multi-sensor validation in diverse forest conditions is a priority.

3.5. Interpreting the Decision-Oriented Framework

The comparative synthesis presented in the decision-oriented conceptual framework highlights that GNSS positioning performance in forest environments should be interpreted because of the interaction between the complexity of the environment and the chosen positioning strategy, not as an intrinsic characteristic of individual positioning technologies.

This perspective emphasizes that improving receiver accuracy alone is insufficient to overcome the limitations imposed by the forest canopy. Operational performance depends on the combined effects of canopy structure, terrain conditions, satellite availability, correction methods, observation strategy, and the ability of different positioning approaches to maintain a reliable solution under varying environmental conditions. The framework suggests that technological evolution in forest positioning is progressively moving from improvements in individual GNSS receivers to adaptive multi-sensor positioning systems. Rather than replacing satellite positioning, complementary sensors increase operational robustness by compensating for the temporary degradation of GNSS observations, allowing for continued positioning in increasingly complex forest conditions.

Therefore, positioning technologies should be evaluated not only by nominal positioning accuracy, but also by operational robustness, implementation requirements, and suitability for specific measurement objectives.

3.6. Operational Implications for Technology Selection in Forest Environments

The decision-oriented framework emphasizes that technology selection for forest positioning should be based on the interaction between environmental conditions, required positioning accuracy, and operational constraints, rather than on the nominal performance of individual GNSS technologies. This perspective is particularly relevant for geodetic and forestry surveys, where canopy density, terrain complexity, and satellite visibility vary considerably within the same study area.

The synthesis indicates that different positioning approaches become progressively more appropriate as environmental complexity increases. Conventional RTK solutions remain appropriate where satellite visibility is favorable, while multi-constellation RTK improves reliability in partial canopy conditions. In environments characterized by dense canopy and complex terrain, integrated multi-sensor approaches can provide greater operational continuity by compensating for the temporal degradation of GNSS observations.

An additional implication concerns the planning of topographic surveys. Positioning performance depends not only on the selected technology, but also on operational factors such as observation duration, satellite geometry, correc-

tion services, availability of control points, and integration of complementary technologies. Therefore, survey design should be considered an essential component of the positioning strategy, especially in complex forest environments (Pirti et al. 2010, Ogundipe et al. 2014, Cățeanu and Moroianu 2024).

Rather than identifying a universally optimal positioning solution, the proposed framework supports the selection of positioning approaches depending on the environmental conditions and operational objectives of each measurement campaign. This perspective can help both researchers and practitioners in selecting strategies that balance accuracy requirements, operational reliability, implementation complexity, and available resources.

3.7. Methodological Challenges and Future Research Priorities

Comparative synthesis highlights substantial methodological heterogeneity: studies differ in receiver, constellations, corrections, observation duration, canopy descriptors, terrain, and accuracy metrics. These differences limit direct comparisons and make it difficult to separate technological progress from experimental design effects (Feng et al. 2021, Wing et al. 2005, Page et al. 2021).

The analysis indicates three priorities: (*i*) standardized protocols for reporting receiver, constellations, corrections, canopy, duration, and error indicators; (*ii*) correction methods adapted to forest degradation mechanisms; and (*iii*) comparative validation of multi-sensor systems in contrasting forest and terrain types. Future progress will depend on both technological innovation and methodological comparability of studies (Faitli et al. 2023, Proudman et al. 2022).

4. Study Limitations

The paper has four main limitations. First, it is a structured critical narrative review, not a systematic review or meta-analysis; selection may be influenced by database coverage and targeted searches, and the reported ranges represent an interpretive synthesis (Page et al. 2021, Wulder et al. 2008).

Second, differences between receivers, constellations, durations, corrections, and error indicators limit comparability and require the values to be interpreted as indicative (Feng et al. 2021, Wing et al. 2005, Pirti 2008, Næsset and Jonmeister 2002).

Third, transferability across regions and forest types is limited by canopy, species composition, season, relief, and local receiver conditions. Fourth, empirical studies and methodological or contextual sources have distinct roles; Prioritizing scientifically evaluated evidence increases credibility but may exclude practical information from gray literature (Sigrist et al. 1999; Deckert & Bolstad 1996; Page et al. 2021).

5. Conclusions

The review shows that GNSS performance in forest environments is determined by the interaction between canopy structure, relief, satellite geometry, receiver class, and observation protocol. Attenuation, multipath propagation, and reduced number of visible satellites explain the consequent deterioration of positioning under canopy (Sigrist et al. 1999; Deckert & Bolstad 1996; Feng et al. 2021). Standalone GNSS and DGPS remain suitable for orientation or metric applications but are vulnerable under dense canopy. RTK and RTK multi-GNSS offer superior performance when the fixed solution can be maintained, but without eliminating the effects of multipath propagation. The integration of GNSS–IMU, LiDAR, UWB, and SLAM increases operational continuity, at the cost of increased complexity and cost (Pirti et al. 2010, Tomaštík and Everett 2023, Cățeanu and Moroianu 2024, Faitli et al. 2023).

The original contribution of the paper lies in organizing the evidence in a decision-oriented framework that links canopy and terrain conditions to the dominant degradation mechanism, the required level of accuracy, and the appropriate technology. No solution is universally optimal; the choice must be calibrated to the measurement objective, correction infrastructure, observation duration, and available resources.

Future research should pursue three directions: (*i*) standardized protocols for reporting receiver, constellations, canopy, duration, and error indicators; (*ii*) correction methods adapted to the forest environment; and (*iii*) comparative validation of multi-sensor systems in contrasting forest and terrain types. Progress will depend on both technological innovation and methodological comparability of studies.

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Točnost GNSS pozicioniranja u šumskom okolišu: strukturirana kritička analiza utjecaja krošnji i strategija ublažavanja

SAŽETAK. Pozicioniranje GNSS-a ispod šumske krošnje i dalje je teško, jer vegetacija slabi signale, pogoduje propagaciji multipata i degradira geometriju satelita. Rad predstavlja strukturirani kritički pregled znanstvene literature objavljene između 1996. i 2025. godine, ažuriran pretraživanjem do 2026. godine. Uspoređuju se autonomni GNSS, DGPS, RTK-GNSS, multi-GNSS i low-cost RTK te GNSS-IMU, LiDAR, UAV, UWB i SLAM pristupi. Rezultati ukazuju na progresivno pogoršanje performansi s gustoćom šumske krošnje. U analiziranim istraživanjima, GNSS pogreške pozicioniranja često dosežu 15–30 m ispod guste krošnje, a RTK multi-GNSS rješenja navode, u usporedivim uvjetima, oko 0,5-2,03 m; rasponi su indikativne, a ne statistički agregirane procjene. Integracija GNSS-a s inercijskim senzorima i LiDAR-om povećava kontinuitet i robusnost, ali operativna validacija ostaje ograničena. Glavni doprinos je okvir usmjeren na odlučivanje koji povezuje krošnje, mehanizme degradacije, tehnologiju i strategije ublažavanja. Istaknuta su tri prioriteta: standardizirano izvještavanje, korekcije prilagođene šumskom okolišu i komparativna validacija multisenzorskih sustava.

Ključne riječi: GNSS, šumska krošnja, točnost pozicioniranja, RTK, LiDAR.

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