Influence of Vegetation Period on Personal Laser Scanning Accuracy for Tree Attribute Estimation in Pedunculate Oak and European Beech Forests

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Abstract

Estimating the main tree attributes using hand-held personal laser scanning (PLS) instruments has been an ongoing area of research. So far, the vast majority of the studies have been conducted, during non-vegetation (leaf-off) period when the scanning view is not obstructed by foliage (Jurjević et al. 2020, Tupinambá-Simões et al. 2023, Vandendaele et al. 2024, Kokeza et al. 2024). Contrary, the number of studies conducted in the vegetation (leaf-on) period is negligible, and therefore, the more detailed comparison PLS studies between leaf-off and leaf-on estimates are still missing. This study investigates the impact of vegetation occlusion on the accuracy of the main tree attributes (diameter at breast height, tree height) in two different forest areas located in Central Croatia, i.e. in the lowland pedunculate oak (*Quercus robur* L.) forests and in the hilly European beech (*Fagus sylvatica* L.) forests. PLS_{HH} scanning and collection of reference ground-truth data (detailed field measurements, static terrestrial laser scanning) in both forest areas were conducted during vegetation (leaf-on) and non-vegetation (leaf-off) periods within the same year, using consistent methodology to ensure comparability. The results show great potential of hand-held personal laser scanning technology in forest inventory. Diameter at breast height can be estimated with great accuracy in both study areas and both vegetation periods. However, the scanning in the leaf-off period produced slightly higher accuracy, which can be attributed to the presence of understorey vegetation in the leaf-on period. The more significant influence of the vegetation period is observed for tree heights, especially in European beech forest on hilly terrain with a greater presence of understorey vegetation. Further research should investigate whether the application of a more appropriate scanning scheme could improve the estimation accuracy of tree heights in such demand and complex forest environment.

1. Introduction

Forest inventory forms the basis of sustainable forest management, providing the data needed to assess timber resources, estimate carbon stocks, monitor biodiversity, and evaluate ecosystem services (Calders et al., 2015). For decades, these inventories have been carried out through direct field measurements, measuring tree diameters at breast height (DBH) with calipers or diameter tapes and estimating tree heights (H) using clinometers or hypsometers. While these methods have proven reliable, they demand considerable time and physical effort, and their results can vary with differences in technique, equipment, and field conditions (Chen et al., 2019). However, emerging research has raised important questions about the consistency and reliability of traditional field-measured tree heights, particularly when these measurements are compared across different forest environments and operational conditions (Jurjević et al., 2020).

Forest scientists and practitioners have long acknowledged the transformative potential of remote sensing technologies in forest inventory applications. This recognition has been validated by remarkable advances in laser scanning (LS) technology, commonly referred to as light detection and ranging (LiDAR), which has become the driving force behind modern remote-sensing-based forest inventory methodologies (Balenović et al., 2021). The last two decades have brought a revolution to this field through LS technology. This technological evolution has been characterised by dramatic reductions in equipment costs, size, and weight, coupled with substantial improvements in platform availability, mobility, and reliability, all supported by exponential growth in computational capacity and data science capabilities (Liang et al., 2022).

LS represents an active remote sensing approach that captures high-precision three-dimensional spatial data through integrated laser scanning, ranging, positioning, and orientation measurement systems. This technology offers several critical advantages for forest inventory applications: it enables direct measurement of three-dimensional tree attributes, provides canopy penetration capabilities that allow simultaneous detection of tree crowns, ground surface, and vertical forest structure, and supports highly automated data processing workflows that enable efficient large-area assessments (Balenović et al., 2021). Terrestrial laser scanning (TLS) marked the first significant breakthrough in forest inventory technology, producing high-resolution, three-dimensional point clouds with millimetre-level precision (Bienert et al., 2018). These systems enable comprehensive forest structure characterisation by capturing precise spatial information about individual trees and forest stands, consistently demonstrating high accuracy for forest inventory applications with reliable estimates of merchantable timber volume and tree attributes (Panagiotidis et al., 2021).

More recently, hand-held personal laser scanning (PLS) has made the technology even more practical. The development and commercialisation of PLS systems has opened new research avenues focused on forest inventory applications, particularly for measuring fundamental tree parameters such as tree detection, stem positioning, diameter at breast height, and total tree height (Balenović et al., 2021). PLS units combine lightweight sensors with SLAM algorithms, allowing a single person to walk through a forest and capture dense 3D data in real time (Hyyppä et al., 2020; Balenović et al., 2021). This portability has drastically increased survey efficiency: up to 30 m² of forest floor per minute compared to less than 1 m²/min with traditional fieldwork, all while maintaining accuracy comparable to TLS (Chen et al., 2019). A significant limitation in realising the full potential of remote sensing data remains the scarcity of affordable, reliable, and comprehensive field reference datasets, which are essential for calibrating satellite and aerial remote sensing products as well as validating allometric models (Liang et al., 2022).

Forest inventory data extraction from LS typically follows one of two methodological frameworks: the area-based approach (ABA), which uses statistical relationships between point cloud metrics and field measurements, and the individual-tree-based approach (ITD), which focuses on detecting, segmenting, and modelling individual trees. While ABA-based Airborne Laser Scanning has achieved operational status in several countries' forest inventory programs, ITD approaches require high-density point clouds that can accurately represent individual tree geometry (Balenović et al., 2021).

The integration of close-range remote sensing technologies has fundamentally transformed forest inventory practices by making previously impossible measurement scenarios feasible, thereby expanding the scope of forest observations through enhanced automation, increased detail resolution, improved accuracy, and more comprehensive data collection capabilities (Liang et al., 2022). Despite considerable progress, the influence of the time of year, particularly the presence or absence of foliage, on the accuracy of LS remains surprisingly underexplored. Nearly all studies have been conducted in leaf-off conditions, when lines of sight are clear (Tupinambá-Simões et al., 2023; Vandendaele et al., 2024; Kokeza et al., 2024). However, forests look very different in the vegetation period, with dense canopies and understorey growth that could scatter or block laser pulses.

The limited research that does exist suggests that leaf-off scanning generally produces better results. For example, Tupinambá-Simões et al. (2024) and Ko et al. (2024) both found notable drops in accuracy under leaf-on conditions. Research comparing conventional field measurements with low-cost close-range remote sensing technologies has demonstrated that traditional tree height measurements may be less reliable than previously assumed, especially in deciduous forest environments (Jurjević et al., 2020). However, these studies focused on specific forest types and locations, leaving unanswered how these effects might vary across different ecosystems and terrains.

The seasonal variation in foliage density and understorey vegetation presents unique challenges for LS systems, potentially affecting point cloud density, occlusion patterns, and subsequent accuracy of tree attribute extraction (Kükenbrink et al., 2022). The selection of appropriate systems and operational protocols significantly influences data quality and attribute extraction accuracy, yet the specific impacts of these choices remain poorly understood in many applications (Liang et al., 2022). Understanding these effects is crucial for forest management practitioners who need to optimise survey timing, cost-effectiveness, and operational feasibility in forest inventory planning.

Critical challenges that require immediate attention include addressing limitations in data completeness and geometric accuracy, as well as overcoming insufficient computational processing capabilities that currently restrict advanced applications and operational implementation. The accumulated research knowledge provides valuable guidance for directing future investigations and potentially integrating H-PLS systems into routine forest inventory operations (Liang et al., 2022; Balenović et al., 2021). The aim of this study was to compare PLS performance in both leaf-on and leaf-off periods across two contrasting forest types in Central Croatia: lowland pedunculate oak (*Quercus robur* L.) and hilly European beech (*Fagus sylvatica* L.) stands, using the same scanning protocol in both seasons. Main tree attributes, including DBH and total height, were measured to evaluate accuracy under different vegetation conditions, assess the influence of vegetation occlusion on measurement precision across forest types and topographies, and apply these findings to recommend optimal timing for LS surveys.

2. Materials and Methods

2.1 Study Area

The study was conducted in two distinct forest areas in central Croatia: in the 101-year-old, lowland pedunculate oak (*Quercus robur* L.) forest stand and in the 88-year-old, hilly European beech (*Fagus sylvatica* L.) forest stand (Figure 1). Both forest stands are even-aged and mixed with other tree species. Furthermore, they are both state-owned and actively managed for sustained timber in 100-year (European beech) and 140-year (pedunculate oak) rotations. For this research, one circular sample plots with a radius of 12.62 m (500 m^2) were chosen from each stand from a larger set of systematically distributed permanent plots (100 x 100 m). (Figure 2).

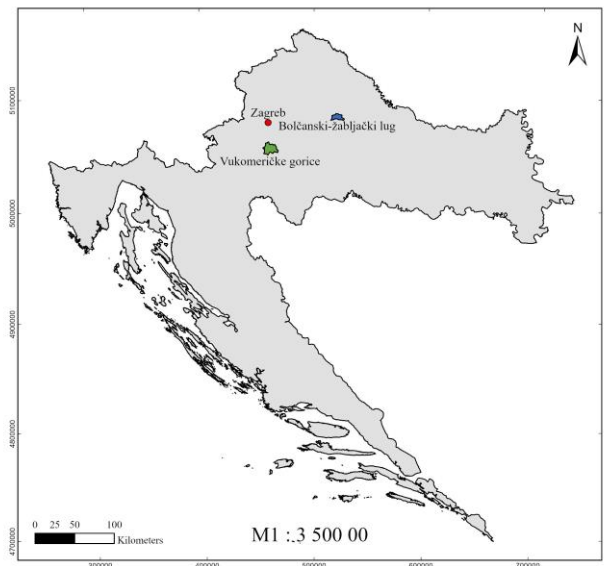
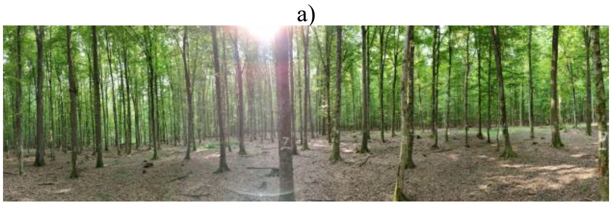


Figure 1. Location of management units in Croatia for pedunculate oak (Bolčanski-žabljački lug) and European beech (Vukomeričke gorice) stands

a)



b)

Figure 2. A panoramic photo of a pedunculate oak plot, taken during non-vegetation (a) and vegetation (b) periods

2.2 Detailed Field Measurements

Detailed field measurements were conducted in January of 2023 and 2024 for the European beech and pedunculate oak forest plots, respectively. For each plot, the coordinates of the plot's centre and ground control points (GCP), used for georeferencing point clouds, were collected. This data was gathered using the Global Navigation Satellite System (GNSS) instrument Trimble R14 (Trimble Inc., Westminster, Colorado, USA), which was connected to the Croatian network of GNSS reference stations (CROPOS) and permanently marked with stakes. The position of each tree in the plot was determined based on its azimuth and distance from the centre, measured using the ultrasonic hypsometer Haglöf Vertex IV (Haglöf Inc., Madison, Mississippi, USA). Furthermore, each tree in the plot was assigned a corresponding number, starting from azimuth zero and proceeding clockwise, and marked with white spray paint. The DBH of each tree in the plot was measured using a diameter tape with a precision of 0.1 centimetre (Table 1). These measurements served as the reference ground-truth data for testing and evaluating the accuracy of PLS-derived DBH.

	Pedunculate Oak N=28, N/ha=220		European Beech N=11, N/ha=560	
	DBH (cm)	H (m)	DBH (cm)	H (m)
Mean	29,3	23,3	68,2	63,1
SD	20,8	7,7	10,0	4,4
Min	6,0	7,3	9,9	12,0
Max	74,8	34,0	55,1	33,8

Table 1. Summary statistics for detailed field measurements collected from both forest plots

2.3 Static Terrestrial Laser Scanning

Static TLS data TLS were collected using a laser scanner in February of 2023 and 2024 for the European beech and pedunculate oak forest plots, respectively. For the European beech forest stand, FARO Focus M70 was used, while for the pedunculate oak stand, FARO Focus Premium 150 was used (FARO Technologies Inc., Lake Mary, Florida, USA) (Figure 3, Table 2).

Figure 3. Static TLS using the FARO Focus M70 scanner on the European beech plot.

	Performance Specifications	
	Focus M70	Focus Premium 150
Range	0.6 – 70 m	0.5 – 150 m
Max Speed	488,000 pts/sec	2,000,000 pts/sec
Ranging Error	± 3 mm	± 1 mm
Field of View	300°x360°	300°x360°

Table 2. Specifications of the static TLS instruments

For both forest stands, a multi-scan approach was used to ensure the coverage of all trees within the plots. The European beech forest plot was scanned from five different positions, while the pedunculate oak plot was scanned from nine different positions (Figure 4). The scanning parameters were set to a resolution of ¼ and a quality level of 4x. Here, the scanning resolution represents one-quarter of the maximum point density in a point cloud, while the quality level indicates the number of laser shots averaged per point. Each scanning position required approximately six minutes, resulting in a total scanning time of about one hour per plot.

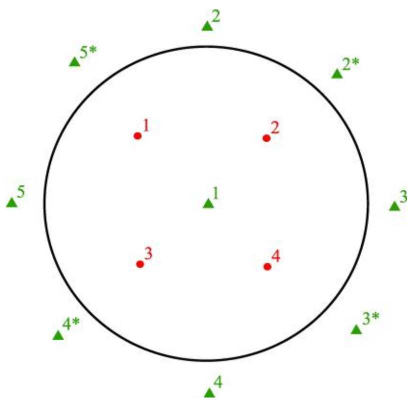


Figure 4. TLS scanning scheme with scanning locations marked by triangles (additional locations for the pedunculate oak plot indicated by *) and spheres marked by dots.

TLS is known for its high accuracy in measuring H. Studies by Calders et al. (2015), Srinivasan et al. (2015), Yurtseven et al. (2019), Disney et al. (2019), and Panagiotidis & Abdollahnejad (2021) have demonstrated strong correlations between H measured using TLS and those obtained through traditional field methods. For this reason, TLS-derived H were used as the reference ground-truth data against which PLS-derived H were compared and evaluated.

2.4 Hand-held Personal Laser Scanning

PLS data were collected using a laser scanner in February of 2023 and 2024 for the European beech and pedunculate oak forest stands, respectively. For the European beech forest stand, GeoSLAM ZEB Horizon was used, while for the pedunculate oak stand, FARO Orbis was used (FARO Technologies Inc., Lake Mary, Florida, USA) (Figure 5, Table 3).

Figure 5. PLS survey using the GeoSLAM ZEB Horizon scanner on the pedunculate oak plot

	Performance Specifications	
	ZEB Horizon	Orbis
Range	100 m	120 m
Speed	300,000 pts/sec	640,000 pts/sec
Precision	6 mm	5 mm
Field of View	360°x270°	360°x290°

Table 3. Specifications of the PLS instruments

Both plots were scanned using a pre-planned walking scheme (Figure 6a). This walking scheme provided optimal scanning coverage of the plots. However, due to the terrain and obstacles, the operator was unable to precisely follow the designated walking path, as illustrated in the scanning scheme depicted in Figure 6b. Consequently, the scanning time for each plot was approximately six minutes during the vegetation period, when there were more obstacles such as shrubs, and about five minutes during the non-vegetation period.

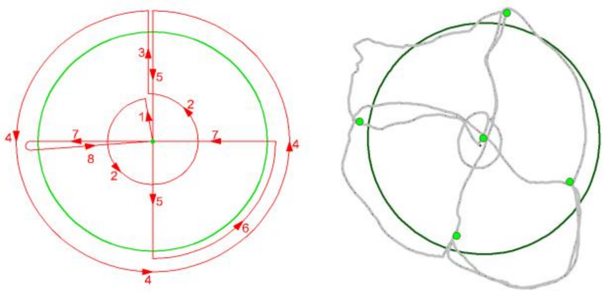


Figure 6. Planned (a) and executed (b) scanning scheme for PLS

2.5 Processing PLS and TLS Data

Prior to the tree attribute extraction, both the TLS and PLS data required pre-processing. TLS data were pre-processed using the FARO Scene software, whereas PLS data were pre-processed using the FARO Connect software. During this step, georeferencing was performed using the GCPs collected in the field. Georeferencing is essential to ensure that the trees from the PLS and TLS point clouds can be accurately matched with those measured in the field. After georeferencing, the point clouds are extracted in LAS format, allowing them to be processed in appropriate point cloud software.

In this case, LiDAR360 v8.0 software (GreenValley International, Berkeley, California, USA) was used to process both the PLS and TLS point clouds. In LiDAR360 software, the point clouds were normalised by transforming the point cloud heights from above sea level to heights above ground level (Figure 7).

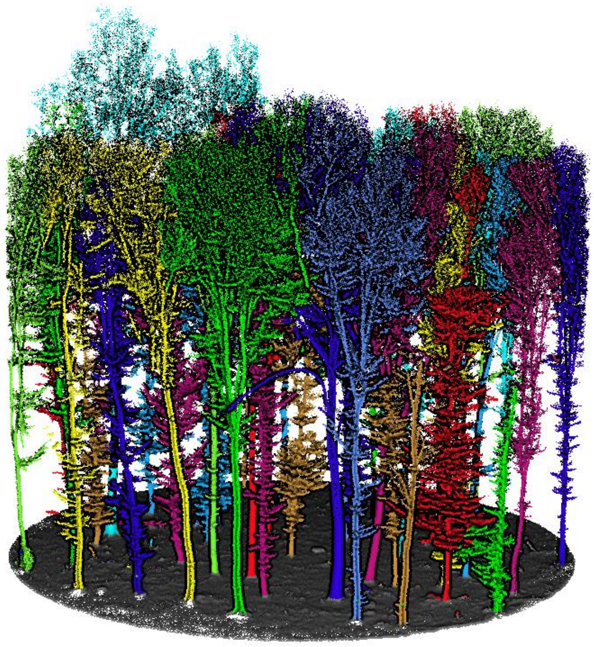


Figure 7. Normalised and segmented point cloud for the pedunculate oak plot in LiDAR360 software

This was done to estimate the DBH at a height of 1.3 meters above ground, as well as to estimate the H from the ground. DBH of each tree were semi-automatically estimated; firstly, by approximate determination of diameter by the operator, which was secondly approximated by the Fit-by-circle method, i.e., by the software algorithm that approximates DBH using the least squares method to fit a circle from the x-y coordinates of input points. Stems fitted by the circle method were used as seed points for individual tree segmentation (Point Cloud Segmentation from Seed Points algorithm). Within the segmentation process, the H were automatically estimated and then manually checked for any inconsistencies or errors.

2.6 Data Evaluation and Analysis

The PLS estimates of DBH and H were evaluated during both vegetation and non-vegetation periods using reference ground-truth data, i.e., detailed field measurements for DBH and TLS data for H. The accuracy of PLS estimates is represented by metrics: mean error (ME), relative mean error (ME%), standard deviation (SD), root mean square error (RMSE), and relative root mean square error (RMSE%).

3. Results and Discussion

3.1 DBH Estimates Accuracy

Both forest plots, featuring pedunculate oak and European beech, show similar accuracy levels for DBH estimates during both the non-vegetation and vegetation periods when compared to detailed field measurements using a diameter tape (Table 4, Figure 9). Both instruments, the GeoSLAM ZEB Horizon (European beech plot) and the FARO Orbis (pedunculate oak plot), demonstrate comparable accuracies of DBH estimates, as have shown studies by Balestra et al. (2024) and Kokeza et al. (2024). Additionally, DBH estimates obtained during the non-vegetation period tend to yield slightly more accurate results than those collected during the vegetation period.

	Pedunculate oak		European beech	
	NV	V	NV	V
ME (cm)	0.33	0.38	0.11	0.26
ME (%)	1.23	1.43	0.37	0.90
SD (cm)	0.34	0.39	0.49	0.56
RMSE (cm)	0.47	0.55	0.50	0.62
RMSE (%)	1.76	2.04	1.70	2.13

Table 4. Estimation accuracy of PLS derived DBH estimates for pedunculate oak and European beech plots during non-vegetation (NV) and vegetation (V) periods

Based on the ME% values, both plots show an overestimation of DBH, regardless of whether estimates are from the non-vegetation or vegetation period. The presence of understory vegetation is the primary factor influencing the differences in DBH estimation accuracy between the vegetation and non-vegetation periods (Figure 8). During the vegetation period, ground layers of vegetation and low shrubs can partially obscure tree stems, which reduces the scanner's ability to capture complete trunk profiles. This occlusion effect is less pronounced in the non-vegetation period when ground-level vegetation is minimal, resulting in higher measurement accuracy for both forest types.

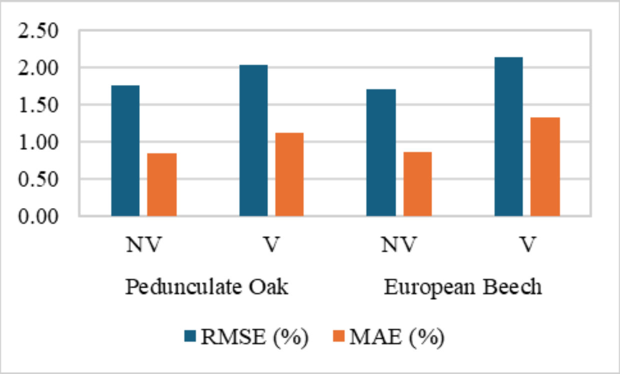


Figure 8. RMSE% and ME% values for PLS derived DBH estimates for pedunculate oak and European beech plots during non-vegetation (NV) and vegetation (V) periods

Despite these seasonal differences, both the GeoSLAM ZEB Horizon and FARO Orbis scanners demonstrated statistically comparable performance across the two forest plots. The lack of significant differences in DBH estimation accuracy between the instruments and forest types indicates that both scanners are well-suited for measuring DBH under varying canopy structures, which corelates with other studies (Chiappini et al., 2022; Tupinambá-Simões et al., 2024). However, it is important to consider that GeoSLAM ZEB Horizon, with slightly worse performance characteristics than Faro Orbis, was used in the European beech plot (11 trees) with a considerably lower tree density compared to the pedunculate oak plot (28 trees).

Our findings are consistent with previous research showing that DBH accuracy and tree detection rates generally improve under leaf-off conditions (Tupinambá-Simões et al., 2024; Kükenbrink et al., 2022). Moreover, the comparable performance of the GeoSLAM ZEB Horizon and FARO Orbis observed here confirms results from earlier comparative studies (Balestra et al., 2024), suggesting that both systems are robust tools for DBH estimation across different canopy conditions.

3.2 H Estimates Accuracy

The H estimates for the pedunculate oak plot are more accurate than those for the European beech plot, both during the non-vegetation and vegetation periods (Table 5, Figure 9). For the European beech plot, there was a noticeable difference in estimation accuracy between the two periods, as suggested by Ko et al (2024). In contrast, the pedunculate oak plot showed no significant difference between the vegetation periods, as suggested by Tupinambá-Simões et al. (2024).

	Pedunculate Oak		European Beech	
	NV	V	NV	V
ME (m)	0.08	0.08	-0.16	-0.08
ME (%)	0.32	0.31	-0.72	-0.35
SD (m)	0.17	0.16	0.37	0.44
RMSE (m)	0.19	0.18	0.40	0.51
RMSE (%)	0.75	0.72	1.78	2.26

Table 5. Estimation accuracy of PLS derived H estimates for pedunculate oak and European beech plots during non-vegetation (NV) and vegetation (V) periods

Based on the ME% values, H is slightly overestimated for pedunculate oak and underestimated for European beech, regardless of whether estimates are from the non-vegetation or vegetation period. The difference in tree density between the plots did not impact the accuracy of the estimations, in fact, the plot with higher tree density yielded more accurate estimations. The lower accuracy observed for beech can be primarily attributed to terrain characteristics (notably steep slopes) and a higher proportion of understorey (especially during the vegetation period), and to a lesser extent to device characteristics, while the discrepancies in accuracy for the H estimates in both plots can be attributed to the varying performance of the GeoSLAM ZEB Horizon and the FARO Orbis.

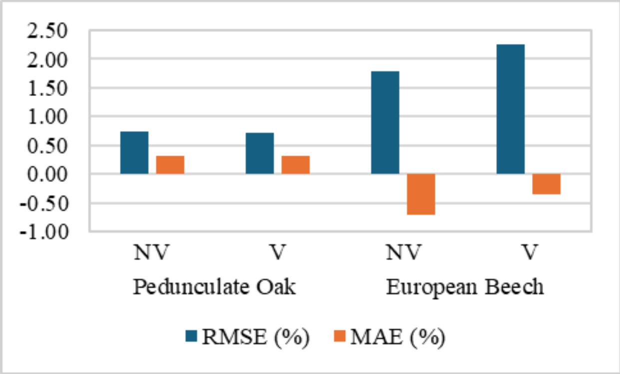


Figure 9. RMSE% and ME% values for PLS derived H estimates for pedunculate oak and European beech plots during non-vegetation (NV) and vegetation (V) periods

The terrain characteristics and performance differences between the GeoSLAM ZEB Horizon and the FARO Orbis likely contributed to these observed discrepancies (Ko et al., 2024). In the European beech plot, denser near-ground and mid-story vegetation during the vegetation period may have partially obstructed the laser's path to the treetops, resulting in a higher likelihood of incomplete canopy returns (Sofia et al., 2021). Conversely, in the pedunculate oak plot, the vertical structure of the vegetation may have been less obstructive, allowing for more consistent H detection across seasons. These results suggest that structural complexity of the stand, rather than tree density alone, is the main factor influencing the accuracy of height estimates. This observation aligns with Aguilar et al. (2024). Interestingly, in some cases denser stands produced better results, likely because reduced understory competition in managed forests improved canopy visibility. While height estimates were generally more accurate in leaf-off conditions, the differences were not always pronounced, and studies based on UAV data even show that leaf-on conditions can outperform leaf-off under certain circumstances (Komárek et al., 2024). This highlights that the effect of seasonality depends strongly on the technology used, forest type, terrain, and measurement objective.

4. Conclusion

This study examines how seasonal vegetation periods influence the accuracy of PLS for forest inventories in pedunculate oak and European beech stands. Results indicate that while PLS is highly suitable for operational forest management, measurement precision, particularly for H, is affected by seasonal vegetation and terrain characteristics.

DBH was measured with consistently high accuracy across both leaf-on and leaf-off periods, with only slight improvements during leaf-off. H estimation showed greater seasonal variation, especially in European beech forests with complex terrain and dense understory, consistent with Ko et al. (2024), who found leaf-off LiDAR data to be more accurate in capturing canopy structure in dense plots. From a management perspective, DBH can be reliably measured year-round, whereas H assessments should be prioritised during leaf-off periods in structurally complex forests.

Future research should involve a greater number of plots with diverse structural and terrain characteristics to draw more definitive conclusions. Future work should also refine scanning protocols for varying vegetation states, evaluate advanced filtering algorithms to reduce seasonal bias, and explore multi-temporal data integration to sustain accuracy and efficiency (Hyyppä et al., 2020). These findings reinforce the operational viability of PLS while highlighting the need to account for seasonal vegetation and terrain characteristics effects in forest inventory planning.

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