Congresos UEx. Actas de Congresos. ISSN: 3101-7177,
vol. 2, 2026, XXI Congreso de la Asociación Española de Teledetección
DOI: https://doi.org/10.17398/3101-7177.2.249

Active and passive 3D sensing for forest stem geometry: Comparing MLS, consumer LiDAR, SfM and Gaussian Splatting

Carbonell Rivera, Juan Pedro [1,2] **Torralba, Jesús** [2] **Crespo-Peremarch, Pablo** [2]
McGlade, James [1] **Simó-Martí, Marina** [2] **Ruiz, Luis Ángel** [2] **Teijido-Murias, Iyán** [3]

[1] Integrated Remote Sensing Studio (IRSS), Department of Forest Resources Management, Forest Science Centre, 2424 Main Mall, University of British Columbia, Vancouver, BC V6T 1Z4, Canadá

[2] Grupo de Cartografía GeoAmbiental y Teledetección (CGAT), Departamento de Ingeniería Cartográfica, Geodesia y Fotogrametría, Universitat Politècnica de València, Camí de Vera s/n, 46022, València, España

[3] SmartForest Research Group, Asturias Raw Materials, Politechnic School of Mieres, University of Oviedo

ORCID: Carbonell Rivera 0000-0002-6724-6780 Torralba 0000-0001-8644-8604 Crespo-Peremarch 0000-0003-2241-4493 McGlade 0000-0001-8830-6626 Simó-Martí 0000-0001-9605-9645 Ruiz 0000-0003-0073-7259 Teijido-Murias 0009-0003-4699-8590

Correspondencia: jp.carbonellrivera@ubc.ca jetorpe@upv.es pabcrepe@cgf.upv.es james.mcglade@ubc.ca msimmar@upv.es laruiz@cgf.upv.es teijidoiyan@uniovi.es

ABSTRACT

Accurate characterization of tree stem geometry is essential for forest inventories, yet conventional field measurements of diameter at breast height (DBH) are limited to a single cross-section and do not capture vertical variability along the trunk. This study compares five approaches for stem characterization in a Mediterranean forest: mobile laser scanning (MLS), consumer-grade iPad-LiDAR, Structure from Motion (SfM) photogrammetry, Gaussian Splatting (GS), and manual field measurements. Data were acquired simultaneously within a 2.5 m radial plot. DBH was estimated through RANSAC-based circular fitting, and stem sections were extracted every 20 cm to assess diameter stability along the trunk. All techniques produced similar mean DBH values closely matching field measurements (23 cm), with MLS achieving the lowest RMSE (1.29 cm), followed by SfM (1.52 cm), GS (1.60 cm), and iPad-LiDAR (2.26 cm). However, marked differences were observed in vertical completeness. MLS captured the full vertical profile of the stems, reaching 14.11 m, whereas SfM and GS from iPhone, and iPad-LiDAR were limited to approximately 6 m or less. The results indicate that although low-cost image-based approaches can provide accurate DBH estimates under controlled conditions, MLS remains the most robust solution for comprehensive vertical stem characterization.

Keywords: *Mobile laser scanning, Structure from Motion, Gaussian Splatting, tree mensuration*

Fecha de recepción: 18 febrero 2026 · **Fecha de aceptación:** 18 febrero 2026

Active and passive 3D sensing for forest stem geometry: Comparing MLS, consumer LiDAR, SfM and Gaussian Splatting

Carbonell Rivera, Juan Pedro [1,2], Torralba, Jesús [2], Crespo-Peremarch, Pablo [2], McGlade, James [1], Simó-Martí, Marina [2], Ruiz, Luis Ángel [2], Teijido-Murias, Iyán [3]

[1] Integrated Remote Sensing Studio (IRSS), Department of Forest Resources Management, Forest Science Centre, University of British Columbia, Canadá.

0000-0002-6724-6780, jp.carbonellrivera@ubc.ca ; 0000-0001-8830-6626, james.mcglade@ubc.ca

[2] Grupo de Cartografía GeoAmbiental y Teledetección (CGAT), Departamento de Ingeniería Cartográfica, Geodesia y Fotogrametría, Universitat Politècnica de València, València, España.

0000-0001-8644-8604, jetorpe@upv.es ; 0000-0003-2241-4493, pabcrepe@cgf.upv.es

0000-0001-9605-9645, msimmar@upv.es ; 0000-0003-0073-7259, laruiz@cgf.upv.es

[3] SmartForest Research Group, Asturias Raw Materials, Politechnic School of Mieres, University of Oviedo.

0009-0003-4699-8590, teijidoiyan@uniovi.es

Abstract: Accurate characterization of tree stem geometry is essential for forest inventories, yet conventional field measurements of diameter at breast height (DBH) are limited to a single cross-section and do not capture vertical variability along the trunk. This study compares five approaches for stem characterization in a Mediterranean forest: mobile laser scanning (MLS), consumer-grade iPad-LiDAR, Structure from Motion (SfM) photogrammetry, Gaussian Splatting (GS), and manual field measurements. Data were acquired simultaneously within a 2.5 m radial plot. DBH was estimated through RANSAC-based circular fitting, and stem sections were extracted every 20 cm to assess diameter stability along the trunk. All techniques produced similar mean DBH values closely matching field measurements (23 cm), with MLS achieving the lowest RMSE (1.29 cm), followed by SfM (1.52 cm), GS (1.60 cm), and iPad-LiDAR (2.26 cm). However, marked differences were observed in vertical completeness. MLS captured the full vertical profile of the stems, reaching 14.11 m, whereas SfM and GS from iPhone, and iPad-LiDAR were limited to approximately 6 m or less. The results indicate that although low-cost image-based approaches can provide accurate DBH estimates under controlled conditions, MLS remains the most robust solution for comprehensive vertical stem characterization.

Keywords: Mobile laser scanning, Structure from Motion, Gaussian Splatting, tree mensuration.

Teledetección 3D activa y pasiva para la caracterización geométrica del fuste forestal: comparación entre MLS, LiDAR de consumo, SfM y Gaussian Splatting

Resumen: *La caracterización precisa de la geometría del fuste de los árboles es esencial para los inventarios forestales; sin embargo, las mediciones de campo convencionales del diámetro a la altura del pecho (DBH) se limitan a una única sección transversal y no capturan la variabilidad vertical a lo largo del tronco. Este estudio compara cinco enfoques para la caracterización del fuste en un bosque mediterráneo: escáner láser móvil (MLS), el LiDAR de un iPad, fotogrametría basada en Structure from Motion (SfM), Gaussian Splatting (GS) y mediciones manuales en campo. Los datos se adquirieron de forma simultánea en una parcela circular de 5 m de diámetro. El DBH se estimó mediante ajuste circular basado en RANSAC, y se extrajeron secciones del fuste cada 20 cm para evaluar la estabilidad del diámetro a lo largo del tronco. Todas las técnicas produjeron valores medios de DBH muy próximos a los medidos en campo (23 cm), siendo MLS la que alcanzó el menor RMSE (1,29 cm), seguida de SfM (1,52 cm), GS (1,60 cm) y LiDAR-iPad (2,26 cm). No obstante, se observaron diferencias significativas en la completitud vertical. MLS capturó el perfil vertical completo de los fustes, alcanzando 14,11 m, mientras que SfM y GS a partir de imágenes adquiridas de un iPhone y el LiDAR-iPad se limitaron aproximadamente a 6 m o menos. Los resultados indican que, aunque los enfoques basados en imágenes y de bajo coste pueden proporcionar estimaciones precisas de DBH bajo condiciones controladas, MLS sigue siendo la solución más robusta para una caracterización vertical integral del fuste.*

***Palabras clave**: Mobile laser scanning, Structure from Motion, Gaussian Splatting, dendometría.*

1. INTRODUCTION

Mediterranean forests are characterized by marked structural heterogeneity, where stem attributes play a central role in determining key dendrometric variables. Diameter at breast height (DBH) remains one of the most widely used parameters in forest inventories, as it directly underpins the estimation of timber volume, biomass, and carbon stocks (Gao & Kan, 2022). However, conventional field-based DBH measurements are restricted to a single cross-sectional observation at 1.3 m above ground, limiting the ability to describe diameter variation along the stem or to quantify trunk inclination and cumulative deviation from verticality.

Recent advances in three-dimensional (3D) reconstruction techniques have enabled detailed geometric characterization of individual tree stems through dense point clouds (Iglhaut *et al*., 2019). Similarly, smartphone devices with integrated LiDAR components have also increased accessibility to 3D data (Gollob *et al*., 2021). Mobile laser scanning (MLS) systems provide high-resolution and repeatable geometric measurements by enabling dynamic data acquisition along continuous trajectories. Compared with static ground-based laser scanning approaches, MLS significantly increases field efficiency, reduces acquisition time, minimizes the need for multiple scan positions, and simplifies post-processing workflows related to scan registration (Iglhaut *et al*., 2019). Despite these operational advantages, MLS systems still represent a considerable economic investment, generally ranging from approximately €5,000 to €60,000 depending on configuration, sensor integration, and positioning capabilities.

At the lower end of the economic spectrum, photogrammetric approaches based on Structure from Motion (SfM) enable 3D reconstruction from overlapping images acquired using any digital camera or smartphone, significantly reducing hardware requirements (Iglhaut *et al*., 2019). More recently, implicit scene representation methods such as Gaussian Splatting (GS) have demonstrated strong performance in generating dense and detailed 3D reconstructions (Fei *et al*., 2025). Conversion of these representations into point clouds enables direct geometric comparison with conventional LiDAR-derived datasets.

Despite the rapid evolution and increasing accessibility of these technologies, few studies have conducted an integrated comparison of MLS, consumer-device LiDAR, SfM photogrammetry, and GS under identical forest conditions. These techniques differ in maximum sensing range, point density, spatial precision, and surface reconstruction characteristics. Differences in acquisition principles (active sensing versus passive image-based reconstruction), point density distribution, occlusion sensitivity, and surface reconstruction strategies may substantially affect stem delineation accuracy and diameter estimation.

The primary objective of this study is to compare the geometric performance of five techniques for stem characterization in a Mediterranean forest environment: MLS, iPad-LiDAR, SfM photogrammetry, GS, and manual field measurements. Specifically, we aim to: (i) analyze differences in point cloud characteristics among the 3D reconstruction techniques; (ii) estimate DBH using each method; and (iii) evaluate the stability and consistency of stem circumference along the trunk by extracting cross-sectional diameters at 20 cm vertical intervals.

2. MATERIAL AND METHODS

2.1. Study area

The study area (Fig. 1) is located within the Serra d'Espadà Natural Park, in the southern part of the province of Castellón, eastern Spain. The experimental site consisted of a circular plot with a 5 m diameter, located within a stand composed of five individuals of *P. pinaster*. The plot included mature pine stems with visible trunks, a shrub understory of varying density, and a forest floor covered by pine litter and scattered woody debris.

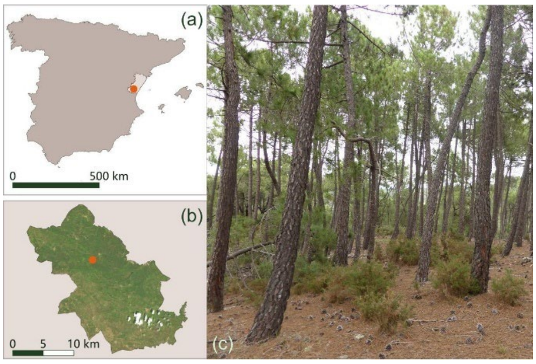

Figure 1. Location of the study area within the province of Castellón, eastern Spain (a). Orthophoto of the Serra d'Espadà Natural Park showing the position of the experimental plot (b). Field photograph of the plot (c).

2.2. Data collection and processing

Data acquisition was conducted concurrently in February 2025. For the iPad-LiDAR and GS datasets, two iPad devices were used: one dedicated to LiDAR scanning and the other for image acquisition intended for GS reconstruction. In contrast, the SfM dataset was generated using an iPhone camera. As shown in Figure 2, the devices were mounted on a rigid handheld photogrammetric base, allowing simultaneous data capture from multiple sensors while maintaining stable relative positioning. This configuration ensured spatial consistency among datasets and minimized temporal discrepancies during acquisition.

To georeference the datasets, polystyrene spheres were distributed within the plot and used as ground control targets. The coordinates of these spheres were measured using GNSS with a Post Processed Kinematic

(PPK) approach. Two Emlid receivers were employed: a Reach RS2+ configured as the base station and a Reach RS3 operating as the rover. Post-processing of GNSS observations enabled centimeter-level positioning of the control targets.

Figure 2. Photogrammetric acquisition base integrating the GS-iPad on the left, SfM-iPhone in the center, and LiDAR-iPad on the right.

2.2.1. MLS

MLS data were acquired using a ZEB-Horizon mobile laser scanner (GeoSLAM Ltd.), which has an acquisiton cost of approximately €35,000. Marker flags were placed around the circular plot to guide the operator in a flower-shape walking trajectory from the plot centre, ensuring complete stem coverage. The system operates at a wavelength of ≈ 905 nm, with a maximum range of about 100 m, a scan rate of up to 300,000 points per second, and a 360° horizontal field of view. According to manufacturer specifications, it provides up to 6 mm relative accuracy under optimal conditions. The capture time was five minutes. Raw MLS data were processed using the manufacturer's SLAM-based software, which performs trajectory estimation, loop closure correction, and point cloud generation through sensor fusion of LiDAR and IMU measurements. Processing time was 10 minutes on a desktop computer.

2.2.2. iPad-LiDAR

An iPad Pro 11″ (2024 model) was used to acquire LiDAR data following a SLAM based approach. The device integrates a solid-state LiDAR sensor operating at ≈ 940 nm, based on a direct time-of-flight principle. The sensor provides a maximum effective range of approximately 4 m under optimal conditions. The 2026 version of the device, which uses the same LiDAR sensor as the 2024 model, is available from €1,099, depending on storage capacity. For data acquisition, the circular plot was divided into four-quadrants, which were scanned independently. This quadrant-based acquisition strategy allowed controlled movement around the stems, improving coverage, reducing occlusion effects, and minimizing SLAM drift. Scanning was performed using the Scaniverse application, which generated three-dimensional point clouds including RGB color information from the integrated camera. The acquisition time per quadrant was approximately 3 minutes (the same as for iPhone-SfM and iPad-GS), with an additional 1 minute of processing on the iPad, allowing real-time visualization of the results during data acquisition. The four-quadrant scans were subsequently merged into a single point cloud using the georeferenced spheres.

2.2.3. iPhone-SfM

The SfM dataset was acquired using an iPhone 15 Pro, recording video at maximum resolution (3840 × 2160 pixels) and 30 frames per second. The iPhone 15 Pro features a 48 MP main wide-angle camera (focal length equivalent to 24 mm, f/1.78 aperture) equipped with a 1/1.28″ CMOS sensor and sensor-shift optical image stabilization. The 2026 version (iPhone 17 pro) of this device, which features the same sensor, is available from €1,319, depending on storage capacity. Individual frames were extracted from the video sequence and processed using Agisoft Metashape. The workflow followed the standard photogrammetric pipeline: feature detection and matching, camera alignment and bundle adjustment, sparse point cloud generation, and subsequent dense point cloud reconstruction through multi-view stereo algorithms. The resulting dense point cloud was scaled and georeferenced using the previously measured polystyrene sphere targets to ensure spatial consistency with the other datasets. Processing time was 20 hours using a PC equipped with an i9-13900KF and an NVIDIA GeForce RTX 4090.

2.2.4. iPad-GS

The GS dataset was acquired using a second iPad Pro 11″ (2024 model) following the same acquisition strategy. Image capture was performed using the Scaniverse application. This iPad integrates a 12 MP wide-angle rear camera (focal length equivalent to 24 mm, f/1.8 aperture) with a backside-illuminated CMOS sensor and Smart HDR processing. GS models the scene as a collection of anisotropic 3D Gaussians, each parameterized by spatial position, orientation, opacity, and radiometric attributes. This representation enables efficient optimization of a continuous volumetric model and high-quality surface reconstruction. For geometric comparison with the other datasets, the optimized Gaussian representation was converted to a discrete 3D point cloud by sampling the spatial distribution of the Gaussian primitives. The resulting point cloud was georeferenced using the polystyrene sphere targets. The processing time was 2 minutes per quadrant on the iPad, allowing real-time visualization of the results during data acquisition.

2.2.5. DBH and stem sections

Once the point clouds were generated and georeferenced, individual tree stems were manually segmented from each dataset (MLS, iPad-LiDAR, SfM, and GS). First, DBH was estimated. A cross-section centered at 1.30 m along the stem axis was extracted using a 5 cm thick slice. Points within this slice were projected onto a plane perpendicular to the estimated axis, and a circular fit was performed using the RANSAC algorithm to obtain the circumference. Second, the stem diameter sections were derived to evaluate diameter stability along the trunk. Cross-sections were extracted every 20 cm along the stem axis, starting at 0.20 m above the base and extending to the minimum common maximum height shared across all datasets to ensure comparability. For each height, the same 5 cm slicing and RANSAC-based circular fitting procedure was applied.

The resulting DBH and stem diameter measurements were compared against field reference data acquired using a caliper. In the field, two perpendicular diameter measurements were taken at breast height. The reference DBH was calculated as the mean of both measurements.

3. RESULTS AND DISCUSSION

The resulting point clouds exhibited densities of 173,621 points·m⁻², 10,605 points·m⁻², 10,264 points·m⁻², and 10,109,961 points·m⁻² for the MLS, GS, iPad LiDAR, and SfM techniques, respectively. However, this point density was not evenly distributed throughout the scene. As illustrated in Figure 3, although data acquisition was primarily focused on the stem, the MLS system captured well beyond the intended scanned area. The MLS point cloud extended to the full vertical profile of the trees, reaching a maximum height of 14.11 m and reconstructing the entire tree structure rather than only the targeted stem section. In contrast, Gaussian splatting reconstructed up to 6.17 m, iPad LiDAR up to 5.81 m, and SfM up to 5.24 m, indicating a more restricted vertical field of view for these approaches, largely limited to the SfM and GS sampling approach and the iPad LiDAR's limited acquisition range.

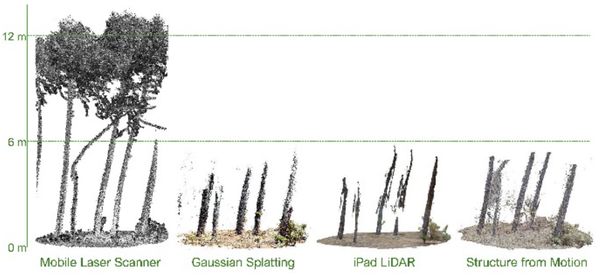

Figure 3. Visualization of the plot for the techniques MLS, GS, iPad-Lidar and SfM.

Table 1 shows that all 3D reconstruction techniques provide mean DBH values highly consistent with field measurements, with negligible differences around the reference value of 23 cm, indicating that breast height diameter can be reliably estimated regardless of acquisition principle. SfM achieved the lowest RMSE relative to field DBH, followed by MLS, GS, and iPad-LiDAR, suggesting that image-based photogrammetry can reach accuracy levels comparable to active laser scanning under controlled conditions. However, clear differences emerge when considering stem section extraction along the trunk. MLS and SfM achieved full section coverage within the common height range, with similar mean section heights and low variability, indicating stable vertical reconstruction. In contrast, GS reconstructed just over half of the potential sections, while iPad-LiDAR showed limited coverage and substantially higher variability, reflecting constraints in vertical completeness and geometric consistency.

Table 1. Summary statistics derived from DBH estimation and stem section analysis up to 5.20 m for each technique.

Method	DBH (mean±SD in m)	RMSE vs Field DBH (cm)	Stem sections (%completeness, mean±SD in m)
Field	0.23±0.08	-	-
GS	0.23±0.08	1.60	52.5%, 0.25±0.08
LiDAR-iPad	0.22±0.07	2.26	25%, 0.39±0.27
MLS	0.23±0.08	1.29	100%, 0.22±0.6
SfM	0.23±0.07	1.52	100%, 0.22±0.7

These results indicate that although DBH estimation alone may suggest comparable performance among techniques, their capacity to characterize stem geometry along the trunk differs considerably, with MLS providing the most complete vertical representation and SfM representing a cost-efficient alternative within a more restricted effective height range.

4. CONCLUSIONS

This study demonstrates that all evaluated 3D reconstruction techniques can reliably estimate DBH, with mean values closely matching field measurements and errors within a few centimeters, and SfM achieves the lowest RMSE under controlled conditions. However, clear differences arise in vertical completeness and stem section consistency: MLS provides the most complete and stable representation of the full trunk profile, while SfM achieves comparable accuracy within a more limited height range. Gaussian Splatting shows intermediate performance, and iPad-LiDAR presents notable constraints in vertical coverage and geometric stability. These results indicate that although low-cost approaches may be suitable for DBH-focused assessments, MLS remains the most robust option for comprehensive stem characterization. Technology selection should therefore consider the trade-off between geometric completeness, operational efficiency, and economic cost. However, it should be noted that the sample size and structural and species diversity of this study were limited. Future studies will include a larger number of plots with greater structural heterogeneity and species diversity.

5. ACKNOWLEDGEMENT

This work was supported by the Canadian Space Agency [Grant 24AO3UBC13], PID2024-158591OB-I00 funded by MICIU/AEI/10.13039/501100011033 and the European Social Fund Plus (ESF+), and the PAID-06-23 Early Research Projects grant from the Vice-Rectorate for Research of the Universitat Politècnica de València (UPV).

6. REFERENCES

Fei, B., Xu, J., Zhang, R., Zhou, Q., Yang, W., & He, Y. (2025). 3D Gaussian Splatting as a New Era: A Survey. *IEEE Transactions on Visualization and Computer Graphics*, *31*(8), 4429–4449. https://doi.org/10.1109/TVCG.2024.3397828

Gao, Q., & Kan, J. (2022). Automatic Forest DBH Measurement Based on Structure from Motion Photogrammetry. *Remote Sensing*, *14*(9), 2064. https://doi.org/10.3390/rs14092064

Gollob, C., Ritter, T., Kraßnitzer, R., Tockner, A., & Nothdurft, A. (2021). Measurement of Forest Inventory Parameters with Apple iPad Pro and Integrated LiDAR Technology. *Remote Sensing*, *13*(16), 3129. https://doi.org/10.3390/rs13163129

Iglhaut, J., Cabo, C., Puliti, S., Piermattei, L., O'Connor, J., & Rosette, J. (2019). Structure from Motion Photogrammetry in Forestry: A Review. *Current Forestry Reports*, *5*(3), 155–168. https://doi.org/10.1007/S40725-019-00094-3