

# Balancing Efficiency and Accuracy in Wood Stem Quality Measurements with UAV 3D Sensing

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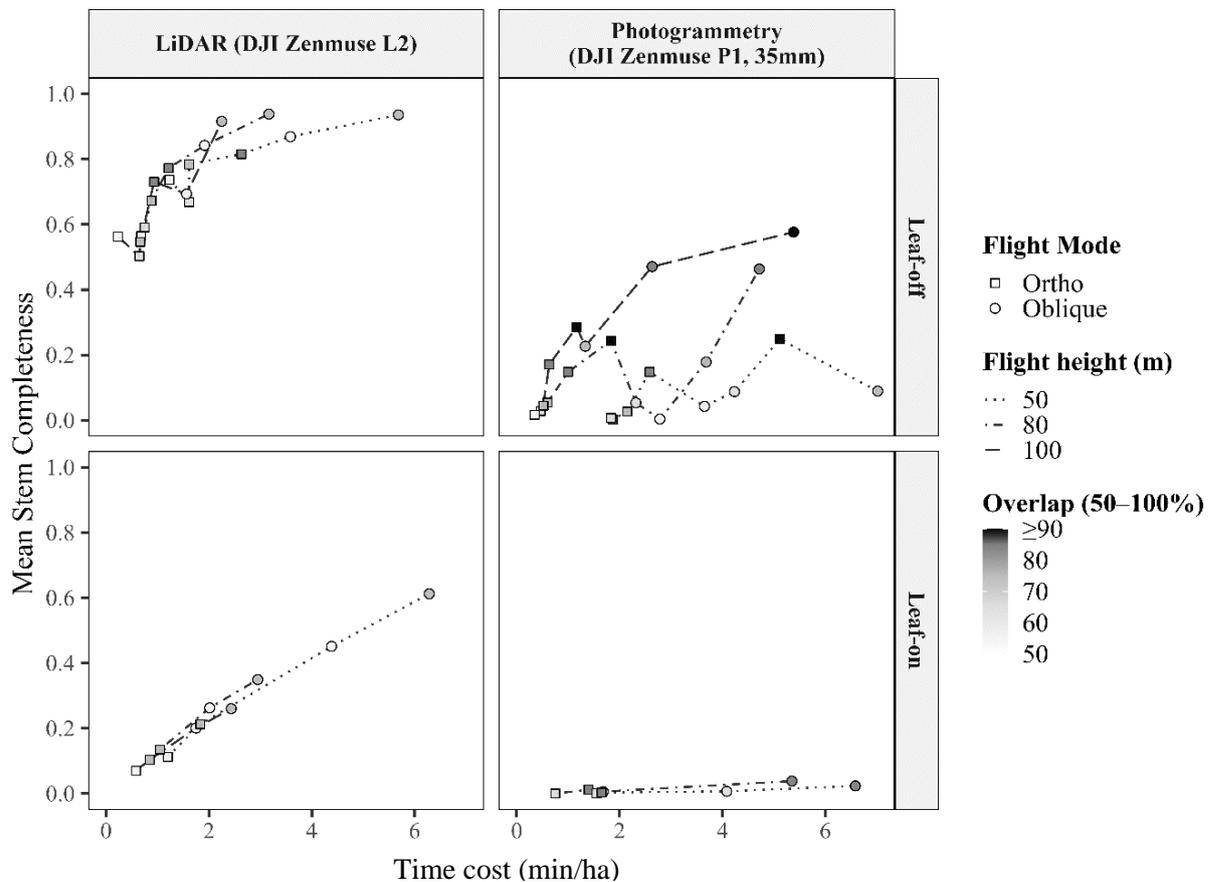
Agile forest management increasingly relies on rapid yet robust assessments of individual-tree attributes to support thinning, harvesting and risk management decisions in near real time. Tree stem quality parameters such as stem curvature, stem taper and crown base height are particularly relevant for economic valuation and for planning stand interventions in a digital-twin framework. Unmanned Aerial Vehicle (UAV) based 3D sensing with LiDAR and Structure from Motion (SfM) has the potential to provide such information efficiently over larger areas. However, there is still little operational guidance on how sensor choice and flight design jointly affect the trade-off between survey efficiency (time per area) and the quality of tree-level stem metrics. This study addresses that gap by systematically evaluating how UAV LiDAR (ULS) and UAV-SfM perform for stem quality assessment under varying flight settings and phenological conditions. The specific objectives are (1) to quantify how sensor type (ULS vs. UAV-SfM), leaf state, and flight mission settings affect stem completeness, stem reconstruction success, and the accuracy and precision of stem-quality metrics relative to TLS ground truth; (2) to identify flight settings that approximate the Pareto frontier between survey efficiency (time per area) and measurement quality; and (3) to translate these relationships into operational recommendations that indicate which survey configurations can realistically deliver a given level of stem-quality accuracy under time constraints relevant for practice.

High-density TLS data acquired with a Riegl VZ-400i multi-return scanner serve as the ground-truth reference for all stem-quality metrics. Individual trees were segmented and their stems reconstructed from TLS point clouds. The UAV used was a DJI Matrice 300 equipped with two different payloads: (1) a Zenmuse L2 LiDAR sensor (ULS) and (2) a Zenmuse P1 full-frame camera (UAV-SfM). For the photogrammetric surveys, flight missions were flown at altitudes between 50 m and 100 m above ground with image overlaps ranging from 50% to 90%. For the LiDAR surveys, flight trajectories were designed to produce different effective scan trajectory densities in the range of approximately 20–80%. Both payloads were flown in nadir-only and oblique flight patterns. All configurations were repeated under both leaf-on and leaf-off conditions. Flight durations were recorded for each mission and normalised by the effectively covered area to derive a measure of survey efficiency (hectares per hour). From the resulting UAV point clouds, tree stems were extracted and reconstructed using a pipeline consistent with the TLS processing. For each tree and flight configuration, we measured (1) stem completeness, defined as the proportion of stem length successfully captured by the UAV point cloud relative to TLS, (2) a binary indicator of successful or failed stem reconstruction, and (3) errors in taper and curvature, calculated as deviations from TLS-derived values. We fitted generalized linear models (GLMs) for multiple response variables: survey efficiency, stem completeness, stem reconstruction success, taper error and curvature error. Sensor type, leaf state and flight mode (nadir vs. oblique) were included as categorical predictors, while mean overlap and flight height were treated as continuous predictors. Based on model predictions, we derived response surfaces and saturation behaviour that describe the trade-off between efficiency and quality.

The assessment of survey efficiency and stem completeness revealed clear trends. Under leaf-on conditions, stem completeness declined for both payloads compared to leaf-off (Figure 1). For UAV-SfM, completeness remained very low and never exceeded about 3.8% of stem length, even with longer flights, higher overlaps or oblique patterns. At comparable efficiency, ULS surveys consistently achieved much higher completeness. Oblique flights improved completeness for both sensors but at the cost of increased flight time, with the largest gains occurring when completeness was already

moderate to high. Increasing overlap enhanced stem completeness up to a saturation point, beyond which additional flight time led to diminishing returns. This saturation threshold varied between sensors and leaf states. Flight altitude had sensor-specific effects: ULS performance was relatively stable across tested heights when overlap was sufficient, whereas UAV-SfM completeness and errors were more sensitive to altitude, especially at low overlaps. Overall, ULS achieved high completeness efficiently, particularly under leaf-off conditions, while UAV-SfM remained constrained to low completeness within similar time budgets. Stem completeness was strongly negatively related to taper and curvature ratio errors, confirming its value as a proxy for measurement accuracy. GLMs explained efficiency, completeness and stem reconstruction success very well (pseudo- $R^2 \approx 0.90-0.91$ ), and taper error reasonably well ( $\approx 0.86$ ), with moderate performance for curvature error ( $\approx 0.67$ ). Mean overlap was a key continuous predictor for completeness and taper error, while sensor type and leaf state were the dominant categorical drivers across models. Interaction analyses showed that the performance gap between ULS and UAV-SfM widened at low overlaps and that photogrammetry was particularly vulnerable to foliage.

Overall, ULS, especially under leaf-off conditions and moderate to high overlaps, can deliver high stem completeness and low error at modest flight times per hectare. Photogrammetry with the UAV-SfM provides much weaker stem reconstructions and saturates at low completeness, even when efficiency is reduced. The resulting models help users select flight configurations close to the Pareto frontier between flight time and stem-quality accuracy, providing concrete, data-driven guidance for UAV-based forest inventories (Table 1, as one example). Because the approach relies on commercially available UAV platforms and simple GLM-based prediction models, it is directly applicable for forest enterprises, public forest administrations, and service providers and can be integrated into existing inventory workflows without specialised infrastructure.



**Figure 1** Mean stem completeness per flight plotted against measured time cost ( $min/ha$ ), with panels separating sensor type and leaf state.

Precision Priority							
Max. Taper Error	Flight Settings					Efficiency	
	Method	Flight Mode	Flight Height (m)	Mean Overlap (%)	Leaf State	$ha/h$	$min/ha$
0.5 cm	ULS (L2)	Oblique	100	70	Leaf-off	29.8	2
	UAV-SfM (P2)						
1.5	ULS (L2)	Nadir	100	50	Leaf-off	180.1	0.3
		Oblique		70	Leaf-on	29.8	2
	UAV-SfM (P2)	Nadir		90	Leaf-off	60	1

Most time efficient configurations

**Table 1** Recommendations for a precision-oriented survey objective. The table provides model derived recommendations: for a specified maximum taper error, it lists configurations that meet the target and ranks them by time efficiency