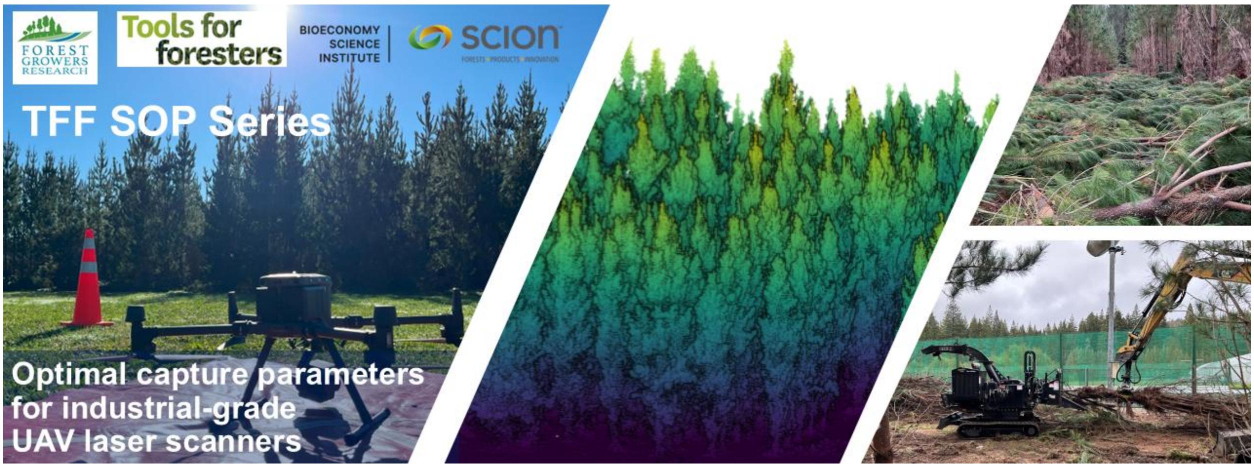

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Optimal flight planning for UAV laser scanner (ULS) operations in forestry.

This SOP was created by Robin J.L. Hartley of Scion as part of the “Tools For Foresters meets AskFGR” project funded by Forest Growers Research (FGR), with co-funding from Scion Group through the Ministry of Business, Innovation and Employment’s Strategic Science Investment Fund (SSIF). Additional content and review provided by Peter Massam, Kevin Park and Honey Jane Estarija of Scion.

1. Objective

This guide provides best-practice guidelines for using unmanned aerial vehicle (UAV) laser scanning (UAV lidar/ULS) in young-to-mid-rotation forestry operations. This SOP provides step-by-step guidance covering:

- Pre-flight setup (GCP placement and base station configuration)
- Sensor selection
- Flight planning parameters (overlap, altitude, scanner settings)
- Stand considerations (effect of understory and stocking on tree measurement)
- Data processing
- Analysis

The included worked example demonstrates the full workflow – from data capture through to interpretation.

2. Setting up for success – Base station and GCPs

Purpose: Ensure high geospatial accuracy and repeatability.

Getting the base station set up correctly is the first and most important step if you want your ULS data to align precisely with other spatial datasets (e.g., photogrammetry, mobile LiDAR). Accurate positioning is essential for high-quality ULS data. The following steps outline how to set up the DJI D-RTK 2 base station to ensure reliable georeferencing during flight operations.

i. Site preparation

- Select a clear, open area near the UAV take-off location.
- Install a **~5 cm square survey peg** firmly into the ground, leaving only 2.5–5 cm exposed.
- Mark the peg with **high-visibility spray paint** (e.g. blue or pink) and highlight the centre with a contrasting colour to aid future relocation. This will ensure that any successive datasets align.
    - ***Tip:*** *Depending on how accurate you require your dataset to be globally, you may want to pre-survey this position using a real-time kinematic global navigation satellite system (RTK GNSS; such as an Arrow Gold etc), which ties the point to the Land Information New Zealand (LINZ) continuously operating reference stations (CORS) network and then input this location into the D-RTK 2 base station (see step iv).*

ii. Base station assembly

- Position the tripod directly over the survey peg and level it using the built-in bubble.
- Attach the extension rod and securely mount the **D-RTK 2 unit**, tightening the lock nut.
- Insert the battery or connect external power. Press and hold the **Power button** until the indicator light turns solid green.
- If using external power, connect the cable and ensure the power source (battery or generator) is stable.

iii. Mode selection and linking

- Press and hold the **Mode button** (right-hand side) to select the appropriate operating mode for your UAV (e.g. 5 flashes for DJI M300).
- Link the remote controller to the D-RTK 2 mobile station. Once connected, tap **Link with Aircraft** in the pop-up window, then press the **Link button** on the aircraft to complete the pairing.

iv. RTK status and coordinate input

- Once linked, the **RTK icon** and satellite count will appear in the status bar of the remote controller. When the icon turns white, RTK positioning is active.
- If manually entering GNSS coordinates: (This process is recommended if you are capturing multi-temporal data from a single site and don't want to see the datasets shift a few meters between captures)
    - Wait for satellite acquisition and for **FIX** status to appear.
    - Navigate to **RTK Settings > Advanced Settings (**default password is 123456)
    - Please input the supplied coordinates and altitude (Ellipsoidal height + D-RTK2 height)
        - ***Note:*** *the D-RTK2 needs coordinates in ellipsoidal height, so make sure to supply altitude in* ***WGS84 ellipsoidal format****.*
        - *The height of D-RTK2 from the tip of the pole on the ground to the centre of the phase of the antenna is 1.8019 m(1660 mm + 141.9 mm, which is pole length plus the height of the GNSS receiver in the unit head) unless the tip of the pole is not touching the ground.*
    - If the D-RTK2 base station is restarted after successful setup, the input coordinates will only be used if they differ from the current position by less than 5 m; otherwise, the system defaults to actual positioning for accuracy.

v. Best practice notes

- Avoid placing the base station near high-power radio sources or reflective surfaces (e.g. water bodies or metal structures).
- Ensure there are no overhead obstructions that could block satellite signals.
- Do not move or adjust the tripod or D-RTK 2 unit after setup—re-levelling will be required.
- Allow at least **2 minutes after startup** for the system to stabilise and acquire position data.

For a visual walkthrough, refer to DJI's instructional video RTK Setup Guide:
https://youtu.be/-pzmpmiD9fs?si=lyK5P5nSej7TAHV9

Tip: If you plan to combine ULS with other datasets (e.g. multispectral photogrammetry or mobile lidar), using Ground Control Points (GCPs) is strongly recommended. GCPs allow for fine-level co-registration and minimise alignment errors

As an example, below is the process for co-registering mobile lidar data from a Hovermap scanner with ULS, following the *CloudReg* method (Hartley et al., 2022; https://doi.org/10.3390/rs14143344)

i. Establish reflective GCPs

- Place at least **5 square targets** (0.5–1 m²), coated in highly reflective material (e.g. 3M reflective sheeting).
- Position GCPs around the **perimeter** and **centre** of the stand, or in open canopy gaps if inside the forest.
- Survey the GCPs using a GNSS receiver to obtain accurate coordinates.
- Additional guidelines for GCP setup are available here: Tools for Foresters SOP – GCPs.

ii. *Capture MLS (below-canopy) and ULS (above-canopy) data*

- **MLS:** Capture below-canopy data using a backpack system (e.g. Hovermap). If the system does not record GNSS, positioning will later be tied to the UAV dataset.
- **ULS:** Capture ULS data following the flight planning and acquisition guidelines in this SOP.

iii. *Confirm visibility and detection of GCPs in point clouds*

- Import both MLS and ULS point clouds into **CloudCompare**.
- Colour the points by **intensity** and filter to display only the highest intensity returns (e.g. ~250 for Hovermap and DJI scanners).
- The reflective targets should now appear clearly in both datasets.

iv. *Co-register the datasets in CloudCompare*

- Use CloudCompare's **Align (point pairs picking)** tool.
- Manually select matching GCPs in the MLS and ULS point clouds.
- Use these as tie-points to align the two datasets.
- Once aligned, check that tree stems and ground features line up correctly across both clouds.

3. Choice of scanner

At the time of writing, two main ULS sensors are in common industry use: the **DJI Zenmuse L1 and the DJI Zenmuse L2**. This SOP focuses on optimising settings for these two scanners.

Note: The DJI L1 is no longer commercially available. Guidance here is provided for users who already own the DJI L1, not as a recommendation to purchase it for new operations.

Comparing the DJI L1 and DJI L2

Below, the key differences between the two sensors are summarised from the report associated with this SOP: "Optimal flight parameters for UAV laser scanning in forestry operations, with insights into the effect of understory and stocking on data quality".

Overall Performance

- **DJI L2 consistently outperformed DJI L1** across all tested metrics, including tree detection, canopy height model (CHM) accuracy, digital terrain model (DTM) accuracy, tree height estimation, and DBH prediction.
- In many cases, **DJI L2 performed comparably to the survey-grade Riegl MiniVUX**, despite being significantly more affordable.

Key Technical Differences

Feature	DJI Zenmuse L1	DJI Zenmuse L2
Beam Divergence	Wider	Narrower (better canopy penetration)
Returns per Pulse	Up to 3	Up to 5 (improved ground detection)
Scan Rate	80–160 kHz	Fixed at 240 kHz (higher point density)
IMU & GNSS Quality	Standard	Improved (better locational accuracy)
Field of View	Narrower	Wider (less edge noise, better crown delineation)
Availability	Discontinued	Current model

Metric-Specific Insights

- **Tree Detection**: Both sensors performed well, but DJI L2 was more stable across different overlaps and return settings.
- **CHM & DTM Accuracy**: DJI L2 showed lower RMSD values, especially when flying low and using all returns.
- **Tree Height Estimation**: DJI L2 provided more consistent and accurate height measurements, particularly in dense or understory-rich environments.
- **DBH Prediction**: DJI L2 yielded higher R^2 values when predicting DBH from 3D crown metrics.

Operational Considerations

- **DJI L1** can still deliver competitive results if flight parameters are carefully optimised (e.g., low altitude, high overlap, all returns).
- **DJI L2** is recommended for most forestry applications due to its robustness, precision, and cost-effectiveness.

Other scanner options

DJI units are not the only ULS sensors available, but they represent a relatively **affordable, effective, and user-friendly entry-level option** for operators already familiar with DJI platforms.

- **Velodyne-based systems (e.g. Hovermap, Zeb Horizon):**
  - Widely used in forestry.
  - Relatively affordable.
  - Less “plug-and-play” than DJI; larger and heavier, which reduces flight times.
  - Less accurate than DJI and high-end systems.
- **YellowScan series (e.g. Mapper, Mapper+):**
  - Designed as plug-and-play payloads for DJI UAVs.
  - Offer streamlined workflows, but at higher cost than DJI’s integrated units.
- **High-end systems (e.g. Riegl MiniVUX series):**
  - Survey-grade accuracy and robustness.
  - Higher cost and typically heavier payloads.
  - Used in this project as a baseline reference for comparison against DJI units.

Based on our results and previous research, some broad performance trends can help guide sensor selection:

- **Higher accuracy** = Survey-grade units (e.g. Riegl MiniVUX) deliver the most precise positioning and geometry, especially for detailed forestry inventory. This is particularly important for terrain modelling and detailed inventory in complex forest structures. However, in the associated study[1] , the DJI L2 performed comparably in many metrics at a fraction of the cost.
- **More returns per pulse** = Sensors with multiple returns (e.g. DJI L2, Riegl) provide better canopy penetration and ground detection in forested environments. This improves detection of intermediate canopy layers and ground points, especially in dense or understory-rich environments. Improved terrain modelling improves height accuracy([1]).
- **Higher pulse density/scan rate** = Increases the resolution of tree and ground surfaces but often comes with higher payload weight and cost. This enhances point cloud density, which supports better segmentation and structural analysis. The DJI L2 offers this increased scan rate at an affordable cost.
- **Integration & usability** = DJI’s L1 and L2 are highly accessible for operators, while Velodyne- and Riegl-based systems may require more expertise but offer greater flexibility. The DJI L2 offers a strong balance of performance and ease-of-use, making it suitable for both research and operational forestry.

[1] Hartley et al., 2025. Optimal flight parameters for UAV laser scanning in forestry operations, with insights into the effect of understory and stocking on data quality. FGR Technical Note.

4. Flight planning

Objective: Maximise point density and minimise occlusion for precise data.

When conducting ULS operations in forestry, there are a few flight parameters that are important to consider, namely altitude, flight line overlap, flight speed, and scanner settings, such as scan rate and the number of returns. All of these flight and sensor parameters have an impact on point cloud density, along with coverage, which are the two points to optimise – gaining optimal coverage, with optimal point density – too much and the data will be too dense and hard to process/store; too little and the data may have gaps that render the point cloud as not truly representative of the actual forest that is being measured. Flight time is another important consideration as increasing overlap and decreasing speed and altitude can exponentially increase flight times. The following guidelines, based on the associated report ([1]), will help to optimise flight planning:

i. Flight speed

Flight speed had a relatively minor impact on most metrics, but slower flights (5 m/s) occasionally improved canopy-based measurements such as tree height and CHM accuracy. This is likely due to increased point density and reduced motion blur. For terrain and DBH metrics, both 5 m/s and 10 m/s performed well, with 10 m/s offering greater efficiency. Overall, speed should be adjusted based on the priority of accuracy versus operational efficiency, with slower speeds favoured when vertical precision is critical.

ii. Flight altitude

Altitude was the most influential flight parameter across all metrics. Lower altitude flights (60 m AGL) consistently produced more accurate results than higher flights (120 m AGL), particularly for CHM, DTM, and tree height estimation. Flying lower increases point density and improves canopy penetration but also increases flight time and data volume. For operational forestry, 60 m is recommended where accuracy is paramount, while 120 m (or other altitudes higher than 60 m) may be acceptable for broader coverage, less detailed analysis, or where visual line of site is compromised (e.g. in older stands).

iii. Number of returns

Using all available returns significantly improved accuracy for terrain modelling and tree height estimation. First returns alone were sufficient for tree detection, as the apex of the tree is typically captured in the first return. However, multiple returns are essential for capturing intermediate canopy layers and ground points, especially in dense or understory-rich environments. For most forestry applications, capturing all returns is recommended to maximise data utility.

iv. Scan rate

Higher scan rates resulted in denser point clouds and improved structural characterisation. The DJI L2, with a fixed scan rate of 240 kHz, consistently outperformed the DJI L1, which operated at 80 or 160 kHz (the minimum and maximum rates for that sensor, respectively). For CHM and DTM accuracy, higher scan rates were particularly beneficial, especially in complex canopy conditions. Although increased scan rates generate larger datasets, the gains in resolution and accuracy justify their use in most scenarios. Notably, higher scan rates can offset reductions in point density caused by increasing speed or lowering overlap, making it a valuable option for balancing accuracy and operational efficiency.

v. Flight line overlap

Overlap had a consistent but moderate effect on accuracy. Higher overlaps (80–90%) improved CHM, DBH prediction, and tree height metrics, while tree detection was less sensitive to overlap. Operationally, overlap had the strongest impact on flight time, with 90% overlap increasing duration by up to 44% compared to 70%. A balance of 80% is recommended for most forestry applications, offering good accuracy without excessive flight time.

vi. Other considerations

Additional flight settings such as terrain-following mode, flight path geometry, and buffer zones around the area of interest, can influence point density and data quality. For example, terrain-following can cause the UAV to slow down or speed up at elevation waypoints, affecting point density distribution. Extending flight paths beyond stand boundaries helps maintain consistent speed and point density across the survey area. These operational refinements should be considered when planning flights for high-accuracy applications.

5. Stand considerations (understory and stocking)

Stand structure significantly influences ULS data quality. The **presence of understory** vegetation was found to reduce the accuracy of DTMs, CHMs, and tree height estimates, due to increased occlusion and reduced ground point visibility ([1]). However, understory had minimal impact on tree detection and DBH prediction, which rely more on upper crown features. **Stocking density** also demonstrated some interesting effects on metric accuracy: tree detection was most accurate in low-density stands, where individual crowns were more distinct, while CHM, DTM, tree height, and DBH accuracy improved in higher density stands due to more consistent canopy surfaces. Although the increased accuracy of tree detection at lower stocking makes sense, some of the trends identified in the report with stocking (such as DBH prediction) were counterintuitive. Further research is needed to understand these effects more clearly. Overall, the findings suggest that flight parameters may need to be adjusted depending on stand conditions, especially in the presence of heavy understory, to maintain optimal data quality ([1]).

6. Operations planning

To aid with field operations planning, an example of a UAV operations plan, along with UAV pre-flight checklist forms can be found in the SOPs section on the Tools for Foresters website: https://www.toolsforforesters.co.nz/tools/standard-operating-procedures

Other useful resources include:
- New Zealand's hub for drone users - AirShare – Aotearoa New Zealand's (AoNZ) official hub for recreational and commercial drone operators, providing tools to plan, log, and request authorisation for UAV flights while ensuring compliance with airspace regulations.
- Flight Advisor – an AoNZ-based online tool that enhances low-level airspace safety by allowing drone and manned aircraft operators to log and view planned operations, helping to reduce the risk of mid-air collisions in uncontrolled airspace. Includes multiple map layers, including AoNZ visual navigation charts (VNCs).
- Drones | aviation.govt.nz - The UAV section of aviation.govt.nz provides official guidance on safe and legal drone operations in AoNZ, including rules under Civil Aviation Parts 101 and 102, training requirements, airspace restrictions, and resources for both recreational and commercial UAV pilots.
- Local and regional council websites are also highly useful sources of UAV-related reference material, particularly useful for forests that are in close proximity to major urban areas, and especially those with airports, e.g.:
  - https://www.tauranga.govt.nz/parks-and-recreation/parks/using-our-parks/flying-drones-or-uavs
  - https://www.dunedin.govt.nz/community-facilities/parks-and-reserves/permission-to-operate-a-remotely-piloted-aircraft-system
  - https://new.aucklandcouncil.govt.nz/en/parks-recreation/get-outdoors/drones-unmanned-aerial-vehicles.html
  - https://ccc.govt.nz/parks-and-gardens/book-a-park/drones-and-remotely-piloted-aircraft-systems

We highly recommend that all pilots conducting UAV operations in forestry, especially those operating a more technical, mid-sized UAV like the DJI Matrice 300 series crafts, should attend a CAA CAR Part 101 certified advanced in-person course to have a thorough understanding of aviation law and how to safely and effectively conduct UAV operations within AoNZ's Airspace

7. Data processing

Once ULS data has been captured, the following steps outline how to process the raw sensor data into a usable point cloud. As this SOP is written to support industry use of specific industrial-grade sensors, these steps are directed at **processing data from the DJI L1 and DJI L2 using the DJI Terra software**. These settings are based on best practice from Scion's internal trials and are suitable for forestry applications, though they have not been formally optimised and users should validate them for their own operational context.

i. Preparing the data

- Insert the SD card into your computer and locate the Data folder that carries the name that was assigned to the flight during flight planning in DJI Pilot.
- Back up the folder to your archive location, then copy it to a working directory for processing.

ii. Starting a new project

- Open **DJI Terra** and navigate to the **Reconstruction** tab.
- Click **New Mission** and select **LiDAR Point Cloud**.
- Name your project appropriately to match the flight or site.

iii. Importing the raw data

- Click the folder icon and navigate to the location of your raw data.
- Select the folder containing the flight data and click **Select Folder**.

iv. Initial checks

- Confirm the **RTK base station coordinates** for each flight. If coordinates are incorrect, the point cloud may not align with satellite imagery.
- Once verified, click **Save**.

v. Recommended processing settings

- **Point Cloud Sampling**: Set to **By Percentage > High (100%)**. This ensures full density is retained for tree metric extraction. Avoid the default “By Distance” setting, which systematically reduces point density, which is not good for tree metric extraction.
- **Scenario**: Select **Point Cloud Processing**.
- **Effective Distance Range**: Set to **2–100 m** to exclude points too close or too far from the sensor.
    - ***NOTE**: these range recommendations are for when flying at 60 m AGL, so if you are flying > 60 m AGL, you should increase this by adding ~50 m onto your flight altitude, e.g. for a 100 m AGL flight, set this to “2-150 m”.*
- **Optimise Point Cloud Accuracy**: Enable this option.
- **Disable the following options**:
    - Smoothing of point clouds
    - Ground point classification
    - DEM and contour generation
- **Advanced Settings**:
    - Output coordinate system: **NZGD2000 / NZTM**
    - Geoid model: **NZVD2016**
    - Height offset: **Nil**
    - Output formats: Enable both **PNTS** and **LAS**
    - Merged output: **Yes**

Once settings are configured, click **Start Processing** and allow DJI Terra to generate the point cloud. When complete, export the **Quality Report** for review.

vi. Exporting and reviewing the point cloud

- Navigate to the **Export** tab.
- Select **3D Models** and **Aerotriangulation**, then click **OK**.
- Choose a destination folder, name the export, and click **Save**.

After export:

- Unzip the results and locate the **LAS file** in the “terra_las” folder.
- Open the LAS file in **CloudCompare** or your preferred GIS software.
    - ***Tip:** CloudCompare is free and well-suited for 3D point cloud visualisation (download here: https://cloudcompare.org/index.html).*
- Perform a visual check for any gross errors (e.g. tree heights significantly off).

- Review the processing report (available in JSON or Markdown format) for any anomalies. While less user-friendly than Pix4D-style reports, these are valuable for advanced users.

If the point cloud passes visual and quality checks, it can be passed into your analysis pipeline (e.g. R-based workflows).

8. Analysis

Once the point cloud has been processed and quality-checked, the following steps outline how to extract forestry metrics using individual tree detection (ITD), crown delineation, and tree-level analysis. These steps are implemented using R-based workflows (within the R statistical programming software) and open-source packages such as lidR and ForestTools. A SOP and example scripts for conducting this are planned for a future project, but the following details the workflow to be undertaken:

i. Individual Tree Detection (ITD)

- Use a **local maxima filtering approach** on the canopy height model (CHM) to identify treetops.
- This method detects peaks in the CHM that correspond to individual tree apices.
- A manually digitised stem map (from field data) can be used to validate detections and classify them as:
  - **True Positives (TP)** – correctly detected trees
  - **False Positives (FP)** – detections where no tree exists
  - **False Negatives (FN)** – missed trees

ii. Crown Delineation

- Apply a **marker-controlled watershed segmentation algorithm** to the CHM using the verified stem map as input.
- This process generates **individual tree crown polygons**, which are used to segment the point cloud into discrete tree objects.
- The ForestTools package in R is commonly used for this step.

iii. Tree-Level Metric Extraction

- For each segmented tree, calculate a range of structural metrics from the point cloud:
  - **Height metrics** – maximum and average tree height
  - **Laser intensity metrics** – reflectance values from different canopy layers
  - **Crown density metrics** – point density within the crown volume
  - **Crown shape metrics** – area, surface area, and volume using a 3D convex hull
- These metrics provide a detailed description of both vertical and horizontal tree structure and can be used for inventory, growth modelling, or DBH prediction.

iv. Tools and Resources

The full processing pipeline has been compiled into an R package: treenotypR

https://github.com/ScionResearch/treenotypR

This package streamlines the workflow from CHM generation to metric extraction and is designed for operational forestry use.