propeller

PPK Accuracy Report

How accurate is Propeller PPK using DJI's M3E drone for photogrammetry and the M350/Zenmuse L2 for lidar?

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Executive Summary

Overview

This document seeks to provide context behind the products that make up Propeller PPK, evaluate the accuracy of the survey deliverables resulting from our lidar and photogrammetry workflows, and deliver recommendations and observations for the applications of both data capture methods. Our accuracy analysis documents the conditions and results of an accuracy field test conducted amidst real-world variables and conditions typically found on a construction site. Through professional surveyor validation, the accuracy analysis confirms that the Propeller PPK solution provides highly accurate measurements within 3 cm for horizontal and vertical data from photogrammetry surveys and 6 cm for vertical models produced from lidar data collection. Consulting for accuracy validation by staff PLS Jim Roake (State of Colorado Lic #: 37898).

Introduction

Purpose

To provide context for the products that comprise Propeller PPK and evaluate the accuracy of Propeller's lidar and photogrammetry workflows, we will cover the following.

01 Background on Propeller PPK
Propeller's PPK workflow utilises the AeroPoint as a base station and ground control point (GCP), and Propeller's processing solution for photogrammetry and lidar data collection methods.

Incorporating the Propeller PPK workflow offers significant cost savings for surveying and mapping operations. Traditional methods often require extensive manpower, time, and equipment, increasing operational costs. The Propeller PPK solution reduces the need for multiple ground control points, minimises field time, and accelerates data processing, which lowers overall project expenses. By integrating this drone technology, companies can achieve higher efficiency, reduce labour costs, and enhance data accuracy, resulting in better project outcomes and financial benefits.

02 Accuracy Test + Analysis for Lidar and Photogrammetry
This report intends to provide confidence that drone measurements are precise and a customer can create a true representation of the work area relative to control points. Propeller customer, Fiore & Sons, allowed the use of an active civil construction project in Castle Pines, Colorado for the study, enabling us to provide an honest assessment of the utility and accuracy of drone surveying amidst real-world variables, including vegetation.

The addition of a professional land surveyor setting checkpoints and validating the accuracy of the Propeller PPK workflow aims to provide clarity and confidence for the surveying community that a PPK-compatible drone, along with an AeroPoint, is a valuable asset in the overall surveying toolbox capable of providing accurate measurements within 3 cm for horizontal and vertical data from photogrammetry surveys and 6 cm for vertical models produced from lidar data collection.

03 Workflow Recommendations + Observations
Propeller's lidar and photogrammetry workflows are complementary, rather than redundant. This report will cover the specific applications of both data capture methods, detailing specific settings and site conditions whereby each performs optimally.

01.

Background on Propeller PPK

The Propeller PPK solution is how Propeller processes the raw GNSS data captured by a compatible drone, in partnership with AeroPoints to log base data for the drone. PPK, or “post-processing kinematic,” means that data from a base station and a drone is collected both simultaneously and independently, and the correction data is then used to adjust the GNSS data during processing instead of using a real-time kinematic (RTK) solution (Pırtı). The Propeller PPK solution is a three-step process of placing an AeroPoint, surveying the site with a PPK-compatible drone, and then uploading the data to Propeller for photogrammetric or lidar processing.

AeroPoint

AeroPoints are Propeller's smart ground control points for fast, highly accurate photogrammetry-based surveying. Version 2.0 has an L1/L2 GNSS chip and is WiFi and Bluetooth enabled. It only requires a minimum GNSS time of 10 minutes.

The maximum baseline distance from a corrections source is 40 km with a maximum capture time of 10 hours, allowing customers to collect numerous smaller projects before uploading or creating complex AeroPoint operations for larger projects

Photogrammetry Processing

Propeller will validate uploaded drone images to ensure they meet recommended settings and include the correct files. Once accepted, the data enters a photogrammetry processing pipeline managed by geospatial experts and engineers. If a survey passes all pipeline checks, it processes automatically. If issues are detected, geospatial experts will troubleshoot the problems with the customer.

After a survey passes initial checks for motion blur and lighting, the software reconstructs the 3D model using camera calibrations. The images colorise the point cloud, while depth maps help reconstruct it. Matching features are detected in the images, and aerotriangulation aligns them correctly.

These matching features are identified using key points and tie points. Key points refer to the feature points on a photo used for alignment, while tie points are the common points among photos used to connect them. Both depend on good image overlap from the drone for the software to identify common features.

Once a sparse point cloud is derived from the images, algorithms automatically mark the ground control points, a process called georeferencing. The Root Mean Square Error (RMSE) is then calculated for each point to show the distance between its original and adjusted coordinates. This value, derived from the square root of the average squared differences, indicates the accuracy of the georeferencing step.

When uploading their dataset, the customer must select a quality assurance threshold to meet their accuracy needs: strict, moderate, lenient, or skip all QA. See *Table 1* for details on each threshold.

When the system cannot automatically identify a ground control point or if a ground control point's RMSE exceeds the threshold, engineers will manually complete the georeferencing and perform photogrammetry troubleshooting. After these steps, the point cloud is ready for export, enabling the generation of digital elevation models, orthomosaics, and contours.

Table 1.

RMSE Thresholds

Option	RMSE Threshold (m)
Strict	0.049
Moderate	0.101
Lenient	0.201
Skip all QA	No data review. Users can review GCP errors in processing report.

Quality Assurance

Before releasing the final models to the customer, Propeller performs quality assurance to ensure survey-grade accuracy. The system automatically checks for absolute accuracy, relative accuracy, and repeatability between surveys. The Quality Assurance details are available for each survey in the Propeller Processing Report.

Absolute accuracy ensures points in the model align closely with real-world positions, which is crucial for precise geographic mapping and engineering. Achieving high absolute accuracy involves accurate georeferencing using ground control points with known coordinates. The Ground Control Summary table quantifies elevation differences between submitted ground control points and the final digital elevation model. This is calculated by subtracting the model's Z coordinate from the elevation values of the corresponding XY coordinates of the ground control points.

Relative accuracy, also known as internal accuracy, evaluates how well points within the model align, emphasising consistency and precision in the survey dataset. This step examines factors such as image quality, misalignment, and model irregularities like holes or warping. The Expected Ground Control Accuracy table indicates the Root Mean Square Errors, which measure discrepancies between uploaded ground control point locations and their positions in the final model.

Repeatability between surveys is assessed by comparing the current dataset with previous surveys in the same area. Propeller's system identifies differences in elevation and horizontal shifts across the site between the current and previous surveys, visualising these variations as a heat map of inconsistent elevations.

During quality assurance, if error values, surface differences, or inconsistencies exceed the chosen threshold, the dataset won't be automatically released and requires review by a geospatial expert. Propeller's experts play a critical role in the dataset processing, intervening at any pipeline stage to manually check and troubleshoot issues detected.

Applications of photogrammetry

Surveying and GIS professionals use photogrammetry to create 3D maps and models for construction, waste management, mining, and aggregates' workflows. Customers use these models for various needs, from verifying existing ground conditions, tracking quantities of material excavated from a quarry, monthly inventory of aggregate material, and monitoring material density and airspace of cells in landfills. The added benefit of aerial data capture is that it allows for improved decision-making, documentation, and reporting of project and site conditions and easily integrates into numerous CAD and GIS applications for further analysis. By leveraging photogrammetry, the earthmoving industry can enhance its operational efficiency, accuracy, and safety.

Lidar Processing

Lidar datasets uploaded to Propeller undergo a processing workflow upon entering the pipeline. Geospatial experts manually handle three main outputs: a classified point cloud (LAZ), a rough orthophoto (TIFF), and a processing report (PDF). Vertical accuracy targets 3 cm, with total accuracy maintained within 6 cm after Root Mean Square Errors (RMSE) meet specified thresholds. The point cloud undergoes denoising based on elevation value bounds, and during this step, a Digital Elevation Model (DEM) and point cloud density maps are created.

Next, the point cloud is classified into ground and non-ground categories (vegetation, buildings, and equipment). An algorithm assesses lidar points' vertical distances from a bare earth DEM, derived from erosion and dilation operations. Points above a set threshold are classified as non-ground, while those below are designated ground, with adjustments made to window size and slope parameters for accurate classification.

Following quality checks on all outputs, a detailed processing report is generated, outlining dataset accuracy and quality metrics.

Applications of Lidar

There are numerous applications for lidar data, including topographic mapping, forestry management, crop monitoring, coastal and marine studies, and infrastructure inspection and maintenance. Point cloud classifications include 18 categories ranging from ground, vegetation, building, water, and other infrastructure elements (NOAA).

The main benefit of lidar for Propeller customers is capturing bare earth beneath vegetation. For the construction industry, lidar data facilitates compliance monitoring, virtual construction models, safety risk mitigation, and the planning stage of new construction. Surveying through the existing vegetation cover will reveal the topography of the surface used to assess stability and estimate quantities of overburden and earthworks toward grading plans (Ball).

02.

Accuracy Analysis for Lidar and Photogrammetry

Site overview map of Fiore & Sons' active civil construction project with GCPs and CPs labled.

Site Conditions

Fiore & Sons' active civil construction project in Castle Pines, Colorado is in various construction phases, from earthwork grading to concrete, asphalt pour, and vertical construction of new homes. The area totals 40 ha with a relief of 45 m. The land cover consists of bare earth, asphalt, shrub/scrub, and grassland/herbaceous vegetation *(Figure 2)* near Newlin Gulch-Cherry Creek *(Figure 1)*, a small ephemeral stream on the eastern and northern sides of the project area (United States Geological Survey).

The lidar and photogrammetric surveys were conducted on May 10th, 2024. Weather conditions throughout the day consisted of temperatures ranging from 4°C to 9°C. Winds were steady and stayed below 16 km/h, with no gusts recorded during the surveys. Cloud cover remained high throughout the day, with only slight breaks during the late morning. During the aerial surveys, cloud cover was heavy in the west, filtering most sunlight, and just before launching the drones, a brief rain shower passed through.

Figure 1. Newlin Gulch-Cherry Creek

Figure 2a. Shrub/scrub and grassland/herbaceous vegetation

Figure 2b. Shrub/scrub and grassland/herbaceous vegetation

Figure 2c. Shrub/scrub and grassland/herbaceous vegetation

Equipment Used

AeroPoint

AeroPoints version 2.0 were used as ground control points (GCPs), checkpoints (CPs), and a base station solution.

Mavic 3 Enterprise

The photogrammetry data collection was conducted with DJI Mavic 3 Enterprise, an industrial-grade mapping drone released in 2022. The sensor consists of a 4/3” CMOS sensor and a 20.9 MP camera with an 84° field of view. The data capture interval of 0.7 seconds and improved lithium polymer battery allow for more efficient data collection and ease of data collection efforts on more significant sites by reducing battery changes and time in the field (DJI).

Matrice 350

Lidar collection was conducted with a Zenmuse L2 sensor mounted on a DJI Matrice 350. This drone is the latest industrial mapping platform released by DJI and has interchangeable payloads for photogrammetry, lidar, thermal, and multispectral data collection (DJI).

Zenmuse L2

With improvements in detection ranges, density penetration, increased returns, and point cloud rates, the L2 can capture smaller objects through thicker vegetation, generating a more accurate digital elevation model. The IMU system provides a real-time yaw accuracy of 0.2° and pitch/roll accuracy of 0.05°, showing operational reliability and precision (DJI).

The L2 also provides the same RGB/camera as the Mavic 3 Enterprise. This functionality allows customers to produce a colorised point cloud and use the sensor for photogrammetry data collection on bare earth.

Base & Rover

Manhard Consulting used a Trimble R12i GNSS as a base and rover combined with a Trimble TSC 7 for data collection. This tried and tested GNSS system, with an RTK specification of 8 mm + 1 PPM horizontal and 15 mm + 1 PPM vertical provides precise measurements.

Methodology

Surveyor Workflow

Propeller and Fiore & Sons provided Manhard Consulting with an existing existing calibration file containing control points for Fiore & Sons' Canyons project in Castle Pines, Colorado. The Trimble R12i GNSS base was set up on Control Point #401. To confirm the base was set up correctly a Trimble RTK TSC7 Rover, receiving corrections from the base, was used to check multiple control points (horizontally and vertically) which resulted in grid deltas of 0.006N x 0.059E x 0.022Z. Propeller provided a KMZ file with AeroPoints and checkpoints. Google Earth and the KMZ file were used to navigate to these locations. At each checkpoint in a roadway, a 2.54 cm masonry nail with white flagging was set into the asphalt, and a Propeller target stencil was used to paint a target with four 30.48 cm arms. For checkpoints on native soil, Propeller's AeroPoint target stencil, and 60d nails with white flagging were used. The R12i Rover, attached to a 2 m rod, TSC7, and bi-pod, measured each point as an observed control point for three minutes. After measuring the 14 checkpoints, the four AeroPoints placed around the site were measured. The collected data was exported as .CSV & .JXL files and provided to Propeller.

Photogrammetry Settings

Propeller determined mission and camera settings by extensively onboarding the Mavic 3 Enterprise drone to produce a consistent model on repeated missions. Propeller conducted over 80 test flights to validate the GNSS receiver and sensor output for full integration into the Propeller PPK workflow. The recommended settings also provide the most efficient data collection methodology for real-world applications on earthmoving projects. The mission and camera settings are in Table 2.

Table 2.

Mavic 3 Enterprise Photogrammetry Mission & Camera Settings

Mission Settings	Set To	Reason
Ortho Collection/Oblique	Ortho Collection	2D collection is sufficient
Ortho GSD	1.6 cm/px	<3 cm GSD for accurate models
Altitude Mode	AGL	Maintain consistent GSD
Terrain Awareness	Real-time Follow	Utilize onboard sensors to maintain AGL during relief change
Route Altitude	61 m	Achieve GSD of 1.6cm/px
Elevation Optimization	Off	Oblique images unnecessary
Safe Takeoff Altitude	Default	No features to avoid during takeoff
Speed	Max Default (51 km/h)	Mission achieved >10 min flight time
Course Angle	0°	Followed a North/South pattern to follow the terrain relief change across the site
Front/Side Overlap Ratio	80	It provides enough overlap so that if some images are missing or are of poor quality while still building a contiguous model.
Margin	0	Mission boundary includes the required area
Photo Mode	Distance	Distance shooting allows the drone to capture images with consistent overlap.
Mode	S (Shutter Priority)	Avoids motion blur
Auto Exposure (AE)	Unlocked	Allows for adjustment of exposure
Shutter Speed	1/800	Due to lower light conditions with cloud cover
Image Ratio	4:3	Utilises entire sensor
Lock Gimbal While Shooting	Enabled	Prevents blurred images
Mechanical Shutter	Enabled	Utilises conventional front and rear shutter. Prevents distortion
Dewarping	Enabled	Improves data accuracy

Why Ground Sampling Distance Matters

Ground sampling distance (GSD) is the resolution of data collected. Essentially, it's the distance from the centre of a pixel to the adjacent pixel in an image. The lower the drone's altitude, the smaller the GSD will be, increasing the resolution of the image collected. For survey-grade accuracy of topography, a GSD of 2 cm or better is recommended. The density of the point cloud is also tied directly to the GSD of the aerial survey, which can impact the overall precision of the 3D model produced from the point cloud, thus degrading the analysis between surfaces (Salach et al.)(Dandois et al.).

Figure 3. Image Resolution Differences (Sitemark.com)

0.5 cm/pixel 1 cm/pixel 2 cm/pixel 4 cm/pixel

Lidar Settings

The Zenmuse L2 lidar sensor was validated and tested extensively by Propeller, conducting 18 test flights with various settings. The final recommended settings are derived from producing the best quality orthophoto from the RGB files and enough points returned to penetrate most vegetated site conditions to return a precise topographic bare earth model without sacrificing accuracy. This report's settings follow the same settings used by Propeller customers in similar situations and are found in Table 3.

Table 3.

Mission Settings	**Set To**	**Reason**
GSD	1.64 cm/px	< 3 cm GSD for accurate models
Route Altitude	61 m	>61 m impacts density and accuracy
Point Cloud Density	207 pt/m^2	>200 pt/m^2 dense recommended
Elevation Optimization	Off	Oblique images unnecessary
Safe Takeoff Altitude	Default	No features to avoid during takeoff
IMU Calibration	Enabled	Necessary for accurate model
Speed	40 km/h	Greater density is needed through thick vegetation
Course Angle	0°	Followed a North/South pattern to follow the terrain relief change across the site
Side Overlap (lidar)	50%	Quality of orthophoto ideal at ≥50%
Front Overlap (Visible)	70%	There is enough overlap for poor or missing images to build a contiguous model still
Margin	0	Mission boundary includes the required area
Photo Mode	Distance	Distance shooting allows the drone to capture images with consistent overlap.
Payload Setting	**Set To**	**Reason**
Return Mode	Triple	Increased return due to dense vegetation
Sampling Rate	240 kHz	A higher number of points was collected to increase the precision of the topographic model
Scanning Mode	Repetitive	Narrows FOV, increasing the accuracy of points
RGB Coloring	Enabled	Creates JPG files to create ortho
Camera Setting	**Set To**	**Reason**
Image Ratio	4:3	Utilises entire sensor
Mechanical Shutter	Enabled	Utilises conventional front and rear shutter. Prevents distortion
White Balance	Daylight	Stayed with default of daylight

Details of Lidar Data Collection

Lidar data collection is very nuanced and will change from site to site, as well as the accuracy requirements for the topographic survey. Propeller's recommendations are a good starting point for capturing the most precise bare earth model. Still, customers must be mindful of variations in vegetation that necessitate a change in flight and payload settings.

- **Speed:** If a site is mostly grass and weeds, the speed can be set to the maximum to decrease data collection time. If thicker vegetation, such as scrub/shrubs and tree canopy cover, is in place, slowing the speed down to 75% or even 50% of the maximum is suggested to allow pulses to reach the surface.
- **Side Overlap:** If the customer isn't concerned with the quality of the orthophoto, an overlap of 20% is sufficient for a bare earth model to be exported into a CAD program for design or estimating purposes.
- **Return Mode:** The canopy height should dictate the data collection settings. Adding triple, quad, or penta return will produce returns through most vegetated conditions. Single and dual should only be used with grass and taller weeds on site.

Results

Photogrammetry Results

During the photogrammetry mission, 1893 images were captured. Propeller's processing pipeline assigns an image quality score based on sharpness, determining 571 as good quality and 1322 as fair quality. All images were included in the processing workflow. The higher number of fair-quality images is attributed to a shutter speed of 1/1000, more suitable for sunny conditions; 1/800 would have been preferable for cloudy conditions. The survey accounted for changing lighting to replicate real-world conditions, aiming to mirror a typical drone surveying experience. Overall, the imagery underwent a 2.2 cm internal alignment and alignment with established ground control points.

Photogrammetry datasets were processed using the known point method with a site calibration and a published coordinate system for comparison purposes. The initial run was processed with 4 AeroPoints as GCPs and the 15 checkpoints (CPs) provided by Manhard Consulting *(Tables 4 & 5)*. Another processing run was completed using 1 AeroPoint as a GCP to evaluate 1 AeroPoint on 40 ha and Propeller's accuracy claim *(Tables 6 & 7)* with 13 CPs used to validate accuracy. During the final processing, CPs 8 and 13 were removed due to high vertical error as they are in heavy brush and were included to validate the lidar processing.

A third processing was run in NAD83(2011)/Colorado State Plane Central (usFT) to validate the accuracy of 1 AeroPoint on 40 ha in a published coordinate system using the Propeller Corrections Network. Due to checkpoint coordinates only provided in a local grid system, the 4 remaining AeroPoints, including the AeroPoint dedicated to lidar data capture, were used as checkpoints to validate the model's accuracy *(Tables 8 and 9)*.

The additional analysis evaluates distance, area, and volume calculations of the static locations to determine consistent internal accuracy (provided in T*ables 10*, *11*, and *12*).

Table 4.

Relative Error of AeroPoint Positions - 4 AeroPoints, Local Grid CRS Survey

Point Location	X Error(m)	Y Error(m)	Z Error(m)	Total Error(m)
KP GCP	0.008	-0.004	0.002	0.009
GCP 2	0.002	0.001	0.002	0.003
GCP 3	0.001	0.000	0.002	0.002
GCP 4	0.007	0.003	-0.004	0.009
			Total Error	0.007

Table 5.

Difference Between The Aeropoint/CP Elevations and the Computed 3D Model - 4 AeroPoints, Local Grid CRS Survey

Point Location	Easting	Northing	Elevation	Surface Elevation	Difference (m)
KP GCP	969370.866	485432.892	1939.341	1939.342	-0.001
GCP 2	969543.086	485487.314	1936.252	1936.252	-0.001
GCP 3	969415.133	485158.642	1949.713	1949.718	-0.005
GCP 4	969633.585	485857.288	1923.757	1923.757	-0.001
				Total Error	0.003

CP	E	N	Z	Surface Elevation	Z Error (m)
CP 1	969621.297	485859.487	1923.608	1923.619	-0.012
CP 2	969530.614	485940.369	1913.011	1913.020	-0.009
CP 3	969544.726	485854.408	1918.157	1918.141	0.016
CP 4	969529.507	485793.690	1920.673	1920.662	0.011
CP 5	969727.307	485707.661	1917.632	1917.633	-0.002
CP 6	969508.132	485628.854	1931.220	1931.216	0.004
CP 7	969269.532	485449.179	1932.306	1932.289	0.017
CP 8	969700.803	485212.176	1931.811	1931.776	0.035
CP 9	969538.724	485171.448	1943.275	1943.269	0.006
CP 10	969264.002	485222.143	1948.165	1948.171	-0.006
CP 11	969475.693	485347.094	1940.772	1940.797	-0.025
CP 12	969505.396	485442.203	1939.085	1939.070	0.014
CP 13	969710.172	485117.497	1933.933	1933.893	0.039
CP 14	969274.743	485136.310	1949.719	1949.722	-0.003
CP 15	969370.884	485432.893	1939.349	1939.342	0.007
				Total Error	0.018

Table 6.

Relative Error of AeroPoint Positions - 1 AeroPoint, Local Grid CRS Survey

Point Location	X Error	Y Error	Z Error (m)	Difference (m)
KP GCP	0.008	-0.005	0.001	0.009
			Total Error	0.009

Table 7.

Difference Between The Aeropoint/CP Elevations and the Computed 3DModel - 1 AeroPoint, Local Grid CRS Survey

Point Location	Easting	Northing	Elevation	Surface Elevation	Difference (m)
KP GCP	969370.866	485432.892	1939.341	1939.344	-0.004
				Total Error	0.004

CP	E	N	Z	Surface Elevation	Z Error (m)
CP 1	969621.297	485859.487	1923.608	1923.615	-0.007
CP 2	969530.614	485940.369	1913.011	1913.011	0.000
CP 3	969544.726	485854.408	1918.157	1918.134	0.023
CP 4	969529.507	485793.690	1920.673	1920.658	0.015
CP 5	969727.307	485707.661	1917.632	1917.625	0.006
CP 6	969508.132	485628.854	1931.220	1931.220	0.000
CP 7	969269.532	485449.179	1932.306	1932.280	0.026
CP 9	969538.724	485171.448	1943.275	1943.267	0.007
CP 10	969264.002	485222.143	1948.165	1948.169	-0.004
CP 11	969475.693	485347.094	1940.772	1940.798	-0.026
CP 12	969505.396	485442.203	1939.085	1939.074	0.011
CP 14	969274.743	485136.310	1949.719	1949.728	-0.009
				Total Error	0.014

Table 8.

Relative Error of AeroPoint Positions - 1 AeroPoint, State Plane

Point Location	X Error	Y Error	Z Error (cm)	Total Error (cm)
KP GCP	0.914	-0.305	0.122	0.010
			Total Error	0.010

Table 9.

Difference Between The Aeropoint/CP Elevations and the Computed 3D Model - 1 AeroPoint, State Plane

Point Location	Easting	Northing	Elevation	Surface Elevation	Difference (m)
KP GCP	969030.038	485262.281	1939.102	1939.103	-0.002
				Total Error	0.002
CP	**E**	**N**	**Z**	**Surface Elevation**	**Z Error (m)**
GCP 2	969202.197	485316.684	1936.013	1936.016	-0.003
GCP 3	969074.289	484988.126	1949.474	1949.488	-0.014
GCP 4	969292.663	485686.531	1923.521	1923.513	0.008
				Total Error	0.016

Photogrammetry Accuracy Analysis

The 3 cm accuracy claims made by Propeller are substantiated by the overall vertical difference between ground control and the topographic model of all three flights. Using multiple checkpoints around the site in varying conditions provides confidence in the Propeller PPK workflow paired with a recommended drone and flight settings to produce an accurate survey for volume tracking and estimating. Distance, area, and volume comparative analyses were completed to determine internal accuracy and to show consistency between coordinate reference systems and processing methods.

The distance calculation used the center of the known point AeroPoint to the remaining three AeroPoints from center to center *(Table 10)*.

Area calculations were derived from two features on site: a static tarp spread wide on the ground and a design file of a design perimeter *(Table 11)*.

Volume calculations were measured using two stockpiles of material on site. The smart volume tool with a -30.48 cm offset was used to set the base to remain as consistent as possible between the local grid system and published coordinate system. Using the Propeller AI tool, the maximum number of vertices were created to ensure a precise tracing of the toe of the piles and the values returned are the volume of cut of material to that base *(Table 12)*.

Table 10.

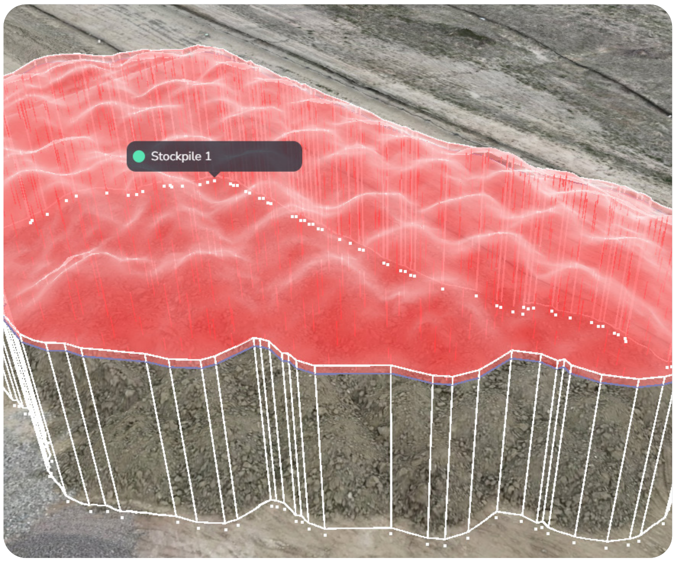
Survey	**KP to GCP 2 (m)**	**KP to GCP 3 (m)**	**KP to GCP 4 (m)**
Local Grid 4 AeroPoints	181.08	279.65	501.64
Local Grid 1 AeroPoint	181.08	279.65	501.64
State Plane 1 AeroPoint	181.02	279.56	501.52

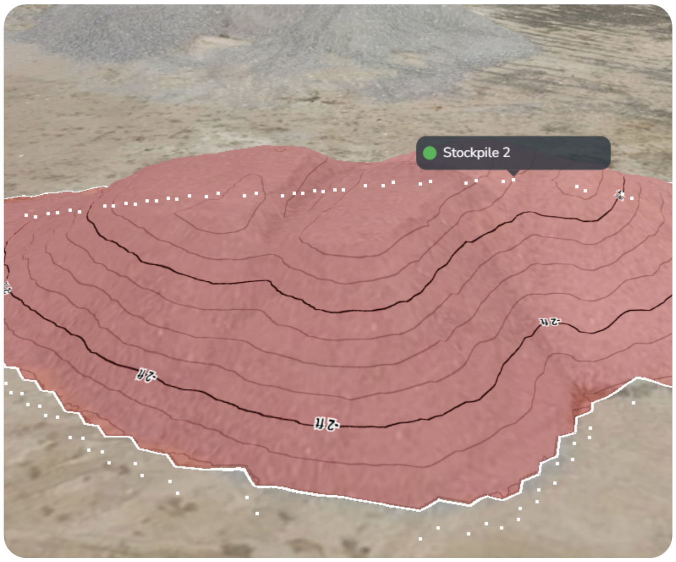
Table 11.

Survey	**Tarp Area (m^2)**	**Design Perimeter (m^2)**
Local Grid 4 AeroPoints	13.35	49,503.49
Local Grid 1 AeroPoint	13.34	49,505.35
State Plane 1 AeroPoint	13.36	49,476.64

Table 12.

Survey	**Stockpile 1 m^3**	**Stockpile 2 m^3**	**Stockpile 1 Variance (%)**	**Stockpile 2 Variance (%)**
Local Grid 4 AeroPoints	471.04	52.91	0.00%	0.00%
Local Grid 1 AeroPoint	473.49	53.06	0.52%	0.29%
State Plane 1 AeroPoint	476.09	52.83	0.55%	-0.43%





Lidar Results

Propeller's accuracy expectation from a lidar dataset collected following best practices and recommended settings is 6 cm. Due to the combination of automated and manual processes in georeferencing, the greatest RMSE is typically on the X and Y axis. At the same time, the vertical accuracy is consistently 3 cm or less. A random sampling of 20 lidar surveys over the last 90 days shows an average RMSE on vertical of 1.8 cm and a total RMSE of 4.6 cm *(Table 13)*.

Table 13.

Survey	Vertical Accuracy (m)	Total Error (m)
1	0.049	0.067
2	0.015	0.049
3	0.009	0.009
4	0.006	0.012
5	0.006	0.006
6	0.012	0.021
7	0.003	0.030
8	0.027	0.088
9	0.021	0.027
10	0.006	0.034
11	0.006	0.107
12	0.024	0.046
13	0.012	0.000
14	0.040	0.049
15	0.027	0.061
16	0.018	0.049
17	0.003	0.034
18	0.040	0.067
19	0.024	0.064
20	0.006	0.094
Avg. RMSE	**0.018**	**0.046**

Propeller's lidar offering is intended to provide a bare earth model through vegetated sites. The focus is the delivery of an accurate ground topo through a wide range of site conditions. The accuracy produced is reflective of this effort. Due to the shift in horizontal accuracy, Propeller recommends using lidar data collection through vegetation, and once a site has been cleared, surveys should be conducted on bare earth using photogrammetry methods.

The two tables below *(Tables 14 & 15)* are the RMSE for the four AeroPoints listed as GCP and the additional checkpoints with overall RMSE for each table's vertical and total RMSE. Due to issues with the orthophoto, checkpoints 2 and 10 were removed from the model verification.

The ground control point summary shows an overall vertically accurate survey with an RMSE of 2.64 cm. Since two checkpoints were removed, 13 remaining checkpoints returned a vertical RMSE of 2.13 cm and an overall error of 3.44 cm.

Table 14.

GCP Table

Point Name	X Error (m)	Y Error (m)	Z Error (m)	Total Error (m)
KP GCP	0.012	0.012	0.029	0.043
GCP 2	0.045	0.008	0.016	0.048
GCP 3	-0.023	-0.019	0.036	0.046
GCP 4	0.012	-0.026	0.021	0.035
		RMSE Vertical	0.027	
		Total RMSE	0.043	

Table 15.

CP Table

Point Name	X Error (m)	Y Error (m)	Z Error (m)	Total Error (m)
CP 1	-0.023	-0.001	-0.009	0.025
CP 3	0.002	-0.026	-0.023	0.034
CP 4	0.002	0.002	-0.051	0.051
CP 5	-0.029	0.013	-0.024	0.040
CP 6	0.052	0.027	-0.020	0.062
CP 7	-0.025	0.007	-0.010	0.027
CP 8	0.006	-0.017	0.013	0.023
CP 9	0.023	0.006	0.010	0.026
CP 11	0.010	0.015	-0.018	0.025
CP 12	0.012	0.011	0.017	0.024
CP 13	0.006	0.042	-0.002	0.043
CP 14	0.008	-0.003	0.017	0.019

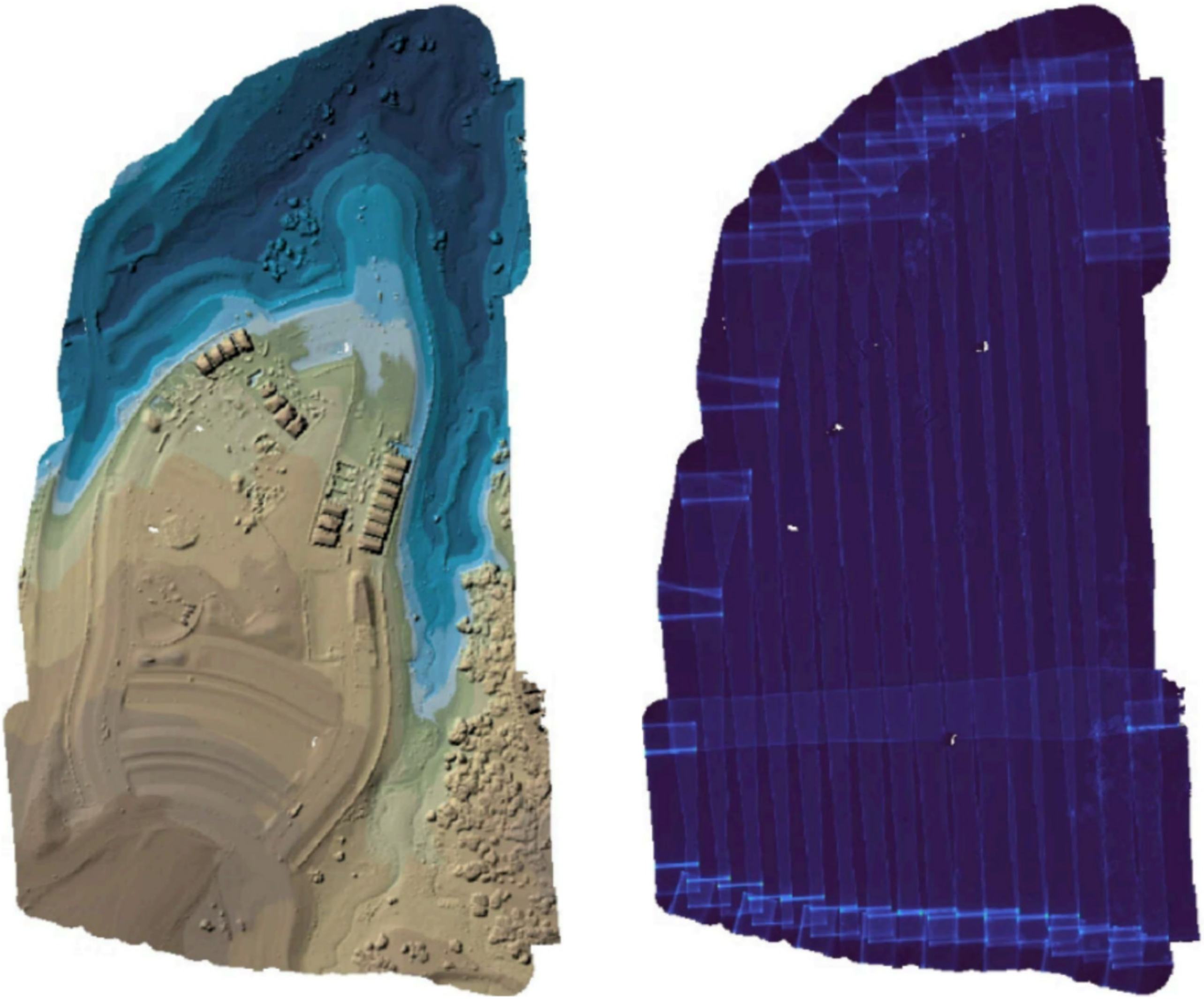
RMSE Vertical	0.021
Total RMSE	0.034

Lidar Accuracy Analysis

The accuracy of the model returned is consistent with previous lidar surveys. GCP and CP RMSE are within 6 cm overall while the vertical RMSE is consistently better than 3 cm. Distance, area, and volume calculations are consistent with the photogrammetry survey. Checkpoints specifically in heavily vegetated locations (CP 3, 4, 5, 9) have an overall RMSE of 3.08 cm with the remaining CPs on asphalt and dirt returning an RMSE of 1.43 cm.

The full processing workload and deliverables produced 406,715,181 points and took 12.2 hours. The point cloud density is 102 pt/m², which resulted in a 3D topographic model of 715,132 TIN faces. An elevation profile and intensity visual are included below in *Figure 4*.

Figure 4.



PLS Results

Once Propeller processed the photogrammetry and lidar data, point clouds were delivered to Manhard Consulting for accuracy validation. Consulting for accuracy validation by staff PLS Jim Roake (State of Colorado Lic #: 37898).

Manhard Consulting produced two reports (*Tables 16 & 17)* comparing two sets of elevation data: one obtained from GPS measurements (Elev (GPS)) and the other obtained from the resulting elevations measured using photogrammetry or lidar (Cloud Elev). The Difference column shows how much the GPS measurements differ from the cloud elevations at each surveyed point.

- Elev (GPS): Lists the elevation heights recorded directly by GPS devices at various locations.
- Cloud (Elev): Shows the elevation heights obtained from either photogrammetry or lidar data.
- Difference: Displays the variation between the GPS and cloud elevations. A positive number indicates the GPS measurement is higher than the cloud, while a negative number means the cloud elevation is higher.

Example (Table 17):

- Row 1 (0.006 m): The GPS elevation is slightly lower than the cloud elevation by 0.006 m.
- Row 6 (-0.024 m): The GPS measurement is 0.024 m higher than the cloud elevation.

These differences help assess how closely the RTK rover and aerial survey methods agree on elevation measurements. Smaller differences generally indicate greater agreement, while larger differences suggest discrepancies between the two methods. These reports are crucial for evaluating the reliability and accuracy of the survey data. The raw data can be downloaded using the link in the Appendix.

Table 16.

Photogrammetry Point Cloud Report - Manhard Consulting

Point (GPS)	Elev (GP)	Cloud (Elev)	Difference (m)	Description of Location
1	1923.608	1923.614	0.006	Dirt Photogrammetry
2	1913.011	1913.202	0.192	Dirt Photogrammetry
3	1918.157	1918.161	0.003	Dirt Photogrammetry
4	1920.673	1920.661	-0.012	Dirt Photogrammetry
5	1917.632	1917.634	0.003	Dirt Photogrammetry
6	1931.220	1931.195	-0.024	Dirt Photogrammetry
7	1932.306	1932.292	-0.015	Dirt Photogrammetry
8	1931.811	1931.825	0.015	Dirt Photogrammetry
9	1943.275	1943.268	-0.009	Dirt Photogrammetry
10	1948.165	1948.178	0.012	Dirt Photogrammetry
11	1940.772	1940.793	0.018	Dirt Photogrammetry
12	1939.085	1939.077	-0.009	Dirt Photogrammetry
13	1933.933	1934.029	0.098	Dirt Photogrammetry
14	1949.719	1949.720	0.003	Dirt Photogrammetry

Table 17.

Lidar Point Cloud Report - Manhard Consulting

Point (GPS)	Elev (GP)	Cloud (Elev)	Difference (m)	Description of Location
1	1923.608	1923.614	0.006	Dirt LIDAR
2	1913.011	1913.126	0.113	Dirt LIDAR
3	1918.157	1918.180	0.024	Dirt LIDAR
4	1920.673	1920.715	0.043	Dirt LIDAR
5	1917.632	1917.674	0.040	Dirt LIDAR
6	1931.220	1931.188	-0.030	Dirt LIDAR
7	1932.306	1932.304	-0.003	Dirt LIDAR
8	1931.811	1931.825	0.015	Dirt LIDAR
9	1943.275	1943.268	-0.006	Dirt LIDAR
10	1948.165	1948.163	0.000	Dirt LIDAR
11	1940.772	1940.780	0.009	Dirt LIDAR
12	1939.085	1939.067	-0.015	Dirt LIDAR
13	1933.933	1933.999	0.067	Dirt LIDAR
14	1949.719	1949.696	-0.024	Dirt LIDAR

Discussion

Accuracy Comparison

A common misconception when researching drone survey technology is that lidar is more accurate than photogrammetry. In a vegetated site condition, that concept is true. However, for customers in civil construction, mining, or waste management, the horizontal consideration is equally important when evaluating the accuracy and precision of an aerial survey. When comparing the Mavic 3 Enterprise to the Zenmuse L2, photogrammetry consistently returns a model with higher accuracy on the horizontal and marginally more accurate vertical values on bare earth and cleared site conditions.

Comparing three surveys, the horizontal, vertical, and total RMSE are listed below for the GCPs and checkpoints separately. As expected, the horizontal and vertical RMSE of the GCPs for the photogrammetry is more precise than the lidar survey. The vertical CP is negligible, which is to be expected in the environment that was surveyed. The total RMSE error strongly favours photogrammetry over lidar on bare earth and mostly cleared sites.

Table 18.

Survey	GCP Vertical RMSE (m)	GCP Horizontal RMSE (m)	GCP Total RMSE (m)	CP Vertical RMSE (m)	CP Horizontal RMSE (m)	Total RMSE (m)
4 AP Photogrammetry	0.002	0.004	0.003	0.018	0.017	0.022
1 AP Photogrammetry	0.001	0.007	0.009	0.014	0.017	0.022
4 AP Lidar	0.027	0.024	0.043	0.021	0.020	0.034

Figure 5, 6, & 7 illustrate the horizontal shift between lidar and photogrammetry surveys. Images 5 and 6 show a point of interest measurement centred directly on CP 1 from the two photogrammetry surveys. Image 7 is the same CP in the lidar survey. The shift between the lidar and consistent locations in the photogrammetry surveys is 4.85 cm.

Figure 5 (4 AP Survey)

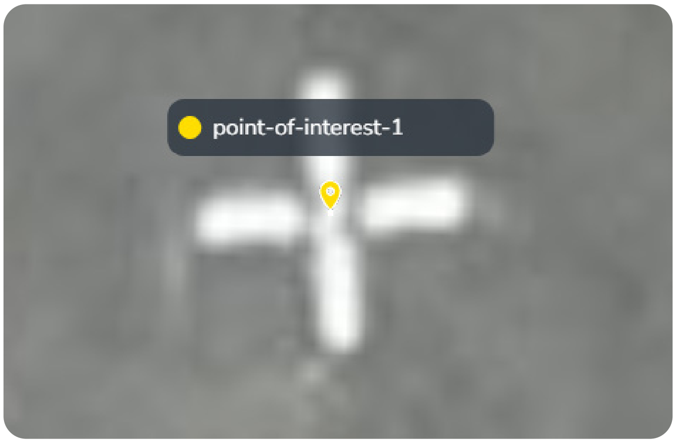


Figure 6 (1 AP Survey)

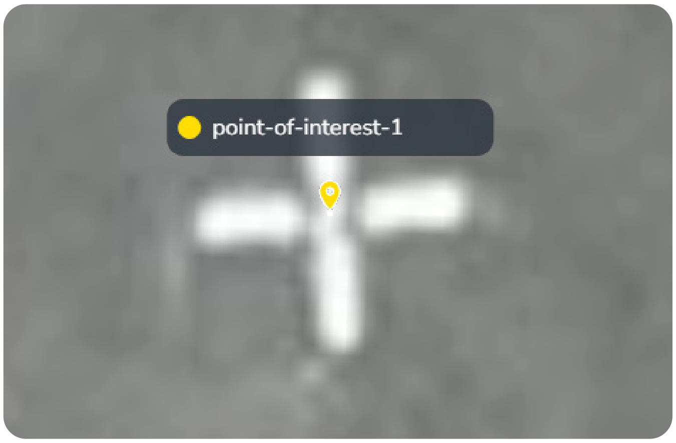


Figure 7 (Lidar Survey)

As discussed in the prior section, the checkpoints in the heavily vegetated areas of the site returned an overall RMSE of 3.08 cm, which is very close to the tolerance allowable for photogrammetry surveys. For this reason, Propeller recommends using lidar surveys through those vegetated sites for estimating purposes. The colourised point cloud (Figure 8) provides an understanding of the bare earth classification in orange *(Figure 9)* from the lidar data, the unclassified remaining points in grey *(Figure 10)*, and the final result of the bare earth model (*Figure 11)* derived from the ground-classified points.

Figure 8.

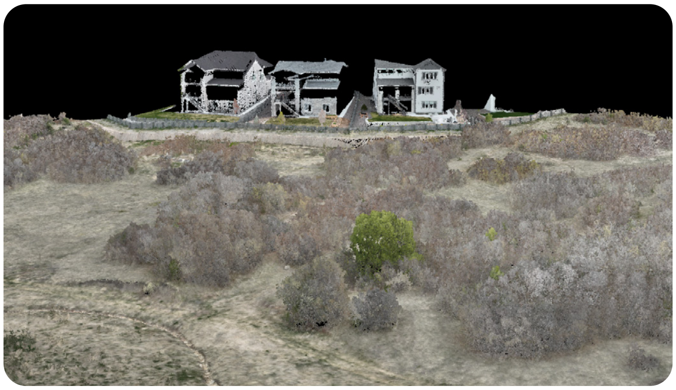


Figure 9.

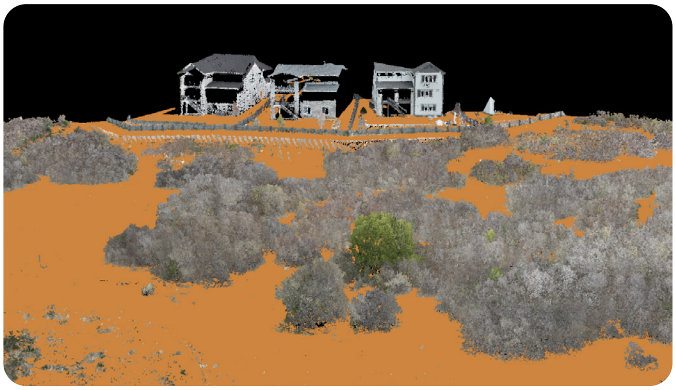


Figure 10.

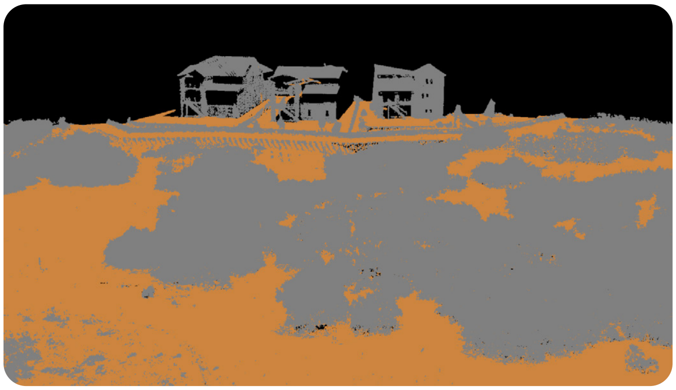


Figure 11.

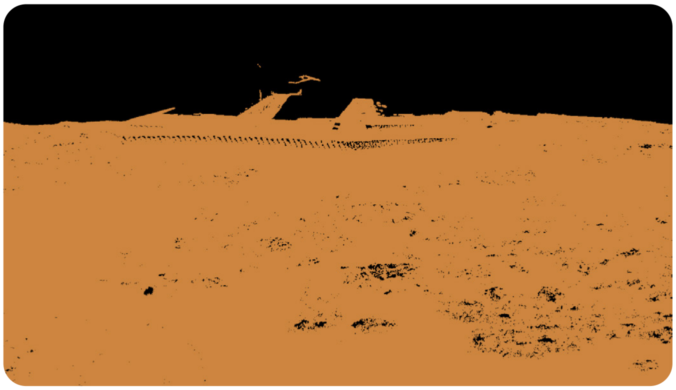
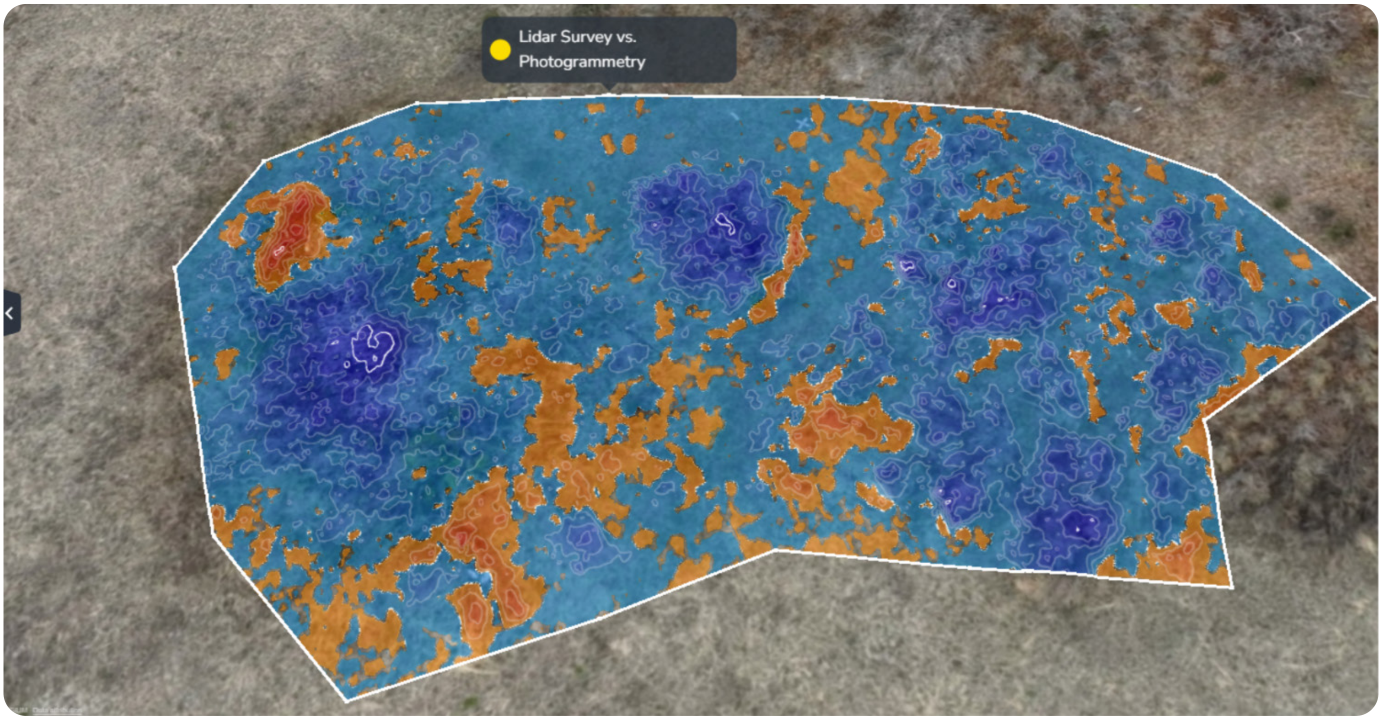


Figure 12.



Performing a surface comparison of a vegetated section between the lidar survey and a photogrammetry survey (Figure 12), the areas in blue indicate areas where the lidar surface would need to “fill” in to meet the photogrammetry survey. This area, which measures ~465 m² yields a fill volume of 23.1 m^3 *(Table 19)*. The areas of cut, which would indicate areas where the lidar surface is above the photogrammetry model, allude to greater geospatial error through the dense vegetation due to greater interpolation.

Additional cross-section analyses on asphalt and graded dirt *(Figures 13 & 14)* yield relatively similar results on vertical calculations where the photogrammetry (blue and orange lines) is more consistent between surveys and the lidar (yellow line) has a slight offset.

Table 19

Fill Volume (m³)	Cut Volume (m³)	Net Volume (m³)	Horizontal Area (m²)
23.1	2.1	21.0	463.5

*Figure 13. (Bare Earth)**

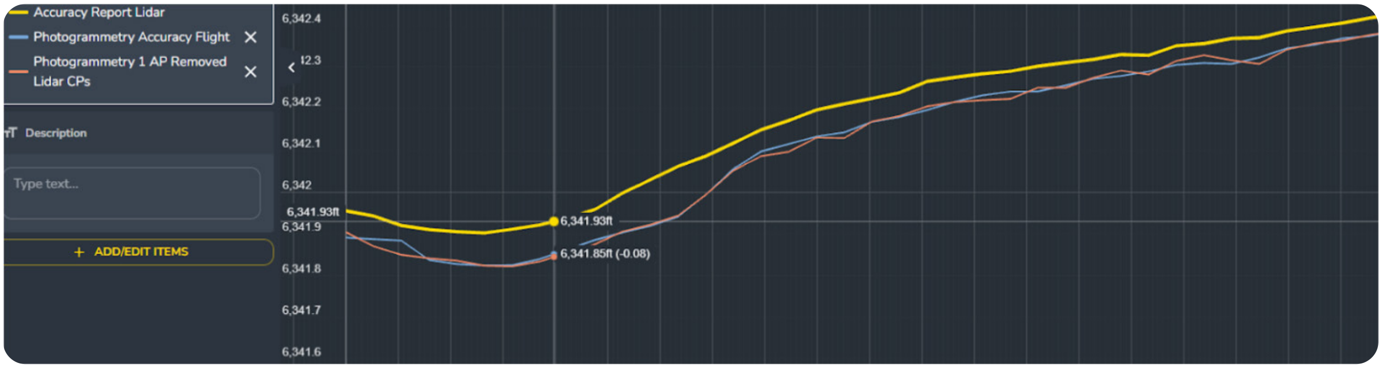
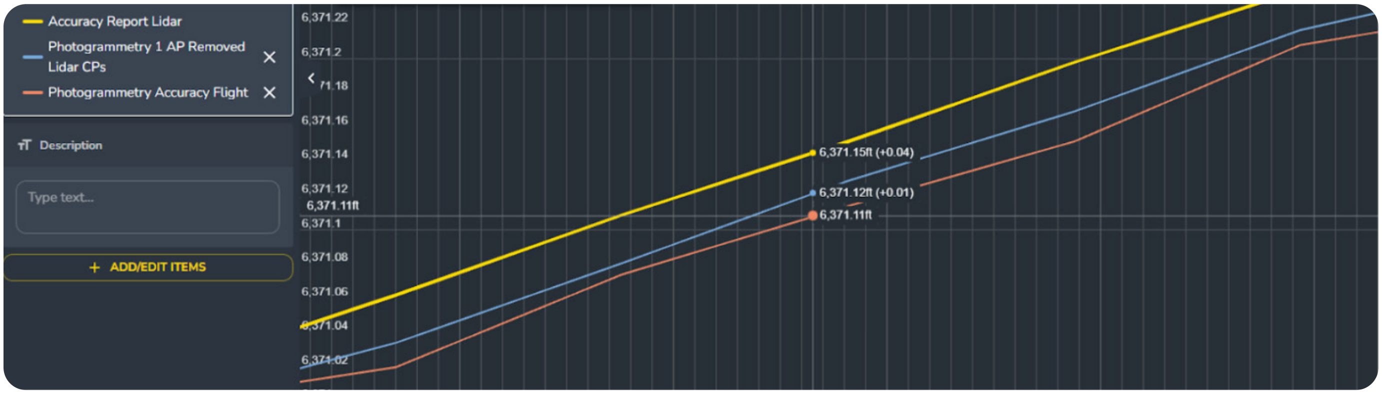


*Figure 14. (Asphalt)**



Due to the increased density of lidar points, surface calculations reveal a smoother surface on both asphalt and graded dirt (*Figures 15 & 16*). This is evident in the exaggerated view of two cross-section comparisons.

*Figure 15. (Bare Earth)**

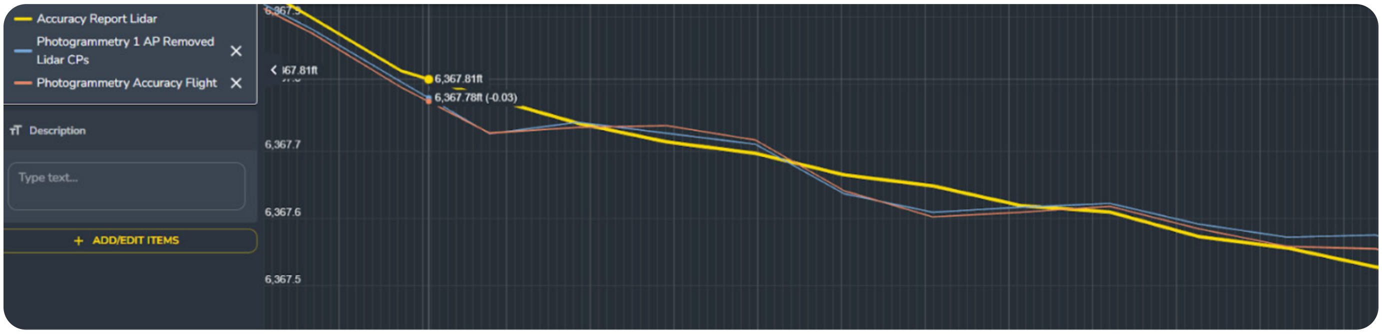
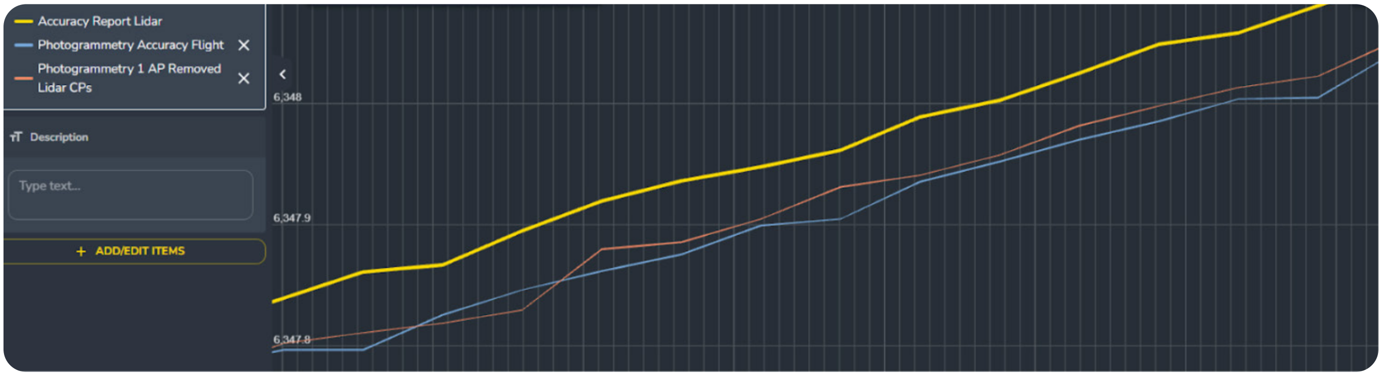


*Figure 16. (Asphalt)**



**Screenshots of Propeller's platform are in imperial units.*

Vertical accuracy is paramount when comparing a drone topographic survey to a design surface or grading plan. Tracking progress between drone surveys for billable purposes on bare earth, the vertical accuracy of photogrammetry and lidar are comparable. However, when evaluating the horizontal accuracy, the difference of a few centimetres against a design surface can have unintended consequences like excavating in the wrong location or planning a concrete sleeve incorrectly. While vertical accuracy is similar, the data collection and processing efficiencies strongly favour photogrammetry.

03.

Workflow Recommendations + Observations

Efficiency

Recommended mission settings for photogrammetry on the Mavic 3 Enterprise platform allow customers to survey 40 ha in approximately 18 minutes. Propeller's service level agreement to return most photogrammetry surveys is 24 hours. In the last year, Propeller has processed 101,606 40-gigapixel AeroPoint PPK datasets and returned 79.9% in 10 hours or less.

Conversely, a lidar data collection with recommended settings and a speed of approximately 32 km/h, the timeframe for data collection is also around 18 minutes due to the decrease in side overlap to 50%. However, the visualisation of the orthophoto is deteriorated and can produce holes. To deliver similar results to the photogrammetry orthophoto paired with a lidar terrain model, it would take approximately 43 minutes to complete the mission. Lidar datasets typically are returned to the customer in 12-16 hours.

Cost Analysis

The price range for photogrammetry drones is quite extensive. The costs increase to narrow the scope to enterprise-level drones with GNSS capabilities, but less than prior models.

Note: All of the USD prices mentioned below are based on DJI RRP May 2024 and are subject to change.

To get the basic package with ±3cm GNSS accuracy, the Mavic 3 Enterprise costs $4337.00. Compact quadcopters range in price from ~$5500-$15,000 (USD) and will vary on manufacturing origin, product functionality, and reliability.

Lidar sensors also have an extensive range of pricing, functionality, and use cases. Costs have come down considerably over the past few years and the Zenmuse L2 has made lidar surveying more attainable in terms of cost. Higher-priced models are available and can range in price from $30k-$50k and some upwards to $200k but with more niche use cases best suited for those sensors. The Zenmuse L2 functionality is sufficient for Propeller's customer base to produce a bare earth model through vegetated sites in most conditions.

It has the flexibility to improve data collection methods for denser vegetation and thicker canopy cover at a reduced cost. The beginning price of pairing the L2 with a basic Matrice 350 package suitable for high-accuracy data collection is ~$25k (USD).

Labour costs associated with data collection and processing are considerably less than a walking topographic survey and turnaround time is much faster with drone data collection methods. A photogrammetry mission consisting of 40 ha necessitates ~30 minutes of preparation time to evaluate air space requirements, ground control placement, and mission planning. Once on site, setup time averages 15 minutes for AeroPoint placement. If additional GCP checkpoints are placed on site and shot in with a data collector, the time will increase depending on the number of collected points. Mission execution of 40 ha is approximately 18 minutes of surveying. Processing and delivery of data will range from 4 to 8 hours. The total turnaround time of a photogrammetry mission from setup to delivery ranges from 5 to 9 hours with direct labour from a customer of ~60 minutes.

DJI Mavic 3 Enterprise
With Care Basic Warranty
$3,628.00

DJI Mavic 3 Enterprise Series
RTK Module
$709.00

Subtotal: $4,337.00

DJI Matrice 350 RTK
Worry Free Plus Combo
$12,559.00

DJI Zenmuse L2 Camera | High-Precision Aerial LiDAR System | Care Basic
$12,430.00

Subtotal: $24,989.00

Table 20.

Data Collection Method	Site Prep (hrs)	Data Collection (No CP/hrs)	Data Processing (hrs)	Total Time (hrs)	Manual Labour (hrs)
Photogrammetry	0.5	0.4	4-8	5-9	0.9
Lidar	0.5	0.4	12-16	13-17	0.9
Walking Topo	0.25	48	0.5	49-50	48.25

Lidar missions are similar in preparation and setup time on site with added processing and data delivery time. The average turnaround time for accurate lidar data is 12-16 hours, making the total time invested in lidar data collection 13-17 hours.

Comparing effort and delivery between a drone platform and a walking topographic survey, on a 40-ha site, the walking topographic survey would take approximately 48 hours of data collection on a 7.62-m grid, using 7.62-m grid spacing and one-second collection intervals. Processing the data to create a 3D topographic model on average is less than an hour, resulting in a total turnaround time of 49-50 hours, 48 of which are manual labour. At eight hours a day, that would take a two-person team three days to complete.

The overall cost of a drone platform to collect data for takeoff quantities and billable volumes is much lower than using a walking topographic survey, including hardware and labour costs *(Table 20)*. The delay in data delivery means the customer is analysing data that is already inaccurate of current site conditions. This delay can also inhibit a proactive response to issues on-site, which can produce cost overruns or necessitate rework.

Site conditions and customer needs will dictate the data collection method used. The cost of photogrammetry is considerably lower than lidar; however, the data returned from a lidar survey is more accurate in vegetated conditions and will give a more precise existing ground condition.

Site Suitability

Propeller recommends using photogrammetry on bare earth or sparsely vegetated sites due to the increase in accuracy on the horizontal datum, efficiency gains, and visual quality of the orthophoto. Propeller's platform also provides options to automatically classify vegetation to be removed from the 3D model, or a customer can utilise the manual terrain cleanup function to remove features from the surface model. The limitation of photogrammetry is that it can map only what it can see. This is why heavily vegetated sites should be flown with lidar.

A site with grasses, weeds, other vegetation, and tree canopy cover should be flown with lidar to create a more precise bare earth model. The ability of the data points to penetrate the vegetation and reduce the distance between known data points produces a more accurate model for site evaluation. The vertical accuracy is most important in this phase of a project, and using photogrammetry increases the interpolation distance between known points. Photogrammetry won't capture bare earth elevations correctly, but will instead capture the top of the vegetation.

Challenges and Limitations

Drone surveying with lidar or photogrammetry is not a panacea for all surveying challenges. More precise calculations are needed for various construction, mining, and waste management workflows. Aerial lidar and photogrammetry are handy tools for volume tracking and grade checks, but they should not be used to evaluate as-built conditions for concrete, asphalt, and other high-precision needs.

Weather also plays a factor in the consistency and accuracy of a drone survey. Temperature, humidity, and wind can all impact the accuracy of the instrument readings on a drone and base station. Additionally, during heavy precipitation events, the ground will be muddy and standing water can also impact volumes calculated from a drone survey. Drones have improved to fly in suboptimal conditions, but there is potential to sacrifice accuracy due to sensor or GNSS data issues.

Areas in restricted or tightly controlled airspace prevent drones from flying or flying at an altitude where data collection efficiencies are lost. There are avenues to receive permission from governing bodies to allow a drone to fly in these areas, but the time spent acquiring the proper documentation and implementation of the hardware may be too cumbersome for inexperienced pilots.

Finally, some areas for the survey may be too small. In the time it would take a pilot to establish minimal ground control, plan the mission, and execute it with enough data to provide accurate results, a walking topographic survey could have been completed.

Conlusion

Summary of Findings

Since Propeller's initial accuracy report in 2018, hardware, sensor capabilities, and the overall cost of drone surveying have improved considerably and will return reliable and accurate data consistently when following guidelines. The improvement of the GNSS chip in the AeroPoint has streamlined the Propeller PPK processing solution and increased the reliability of the data.

This PPK solution has allowed Propeller to offer an accurate and consistent suite of survey data from photogrammetry or lidar data collection methods. Extensive testing by Propeller has determined that the recommended settings and data collection guidelines will return photogrammetry results consistently to within 3 cm on the horizontal and vertical axes. Customers can confidently fly a lidar mission and receive vertical data within 3 cm and horizontal data within 6 cm.

Appendix

Raw Data

The raw data analysed and disussed in this report can be downloaded here.

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