AZ Mohave 2021 Topographic Lidar Project

Lot 6 – Delivery Report

April 28, 2022

Prepared for:

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National Geospatial Technical Operations Center

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TASK ORDER: 140G0221F0156

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Introduction

Optimal GEO, Inc. was tasked by the United States Geological Survey to acquire and process QL2 topographic LiDAR data for 1,152 square miles covering the county of Mohave, AZ. This LiDAR data will be used to produce a high-resolution bare earth Digital Elevation Model of the entire project area. This report describes the data acquisition, ground survey, data processing, quality control, and data validation activities related to producing the final deliverables for this project.

The LiDAR data were processed in accordance with this task order's Statement of Work, as well as the USGS' NGP Lidar Base Specification 2020, Revision A.

Project Team

Optimal GEO, Inc., serving as the prime contractor of this task order, was responsible for managing all project related activities. Optimal GEO was directly responsible for the topographic lidar post acquisition QA/QC, initial automated classification, manual editing of the lidar data and breakline generation and performing QA/QC on all final deliverables. All ground survey activities required to collect ground control and accuracy checkpoints were performed by Woolpert, Inc. The data acquisition and calibration were performed by Woolpert, Inc.

Coordinate Reference System

The lidar data and derived products were delivered in the following reference system.

Horizontal Datum: North American Datum 1983, 2011 adjustment (NAD83 (2011))
Vertical Datum: North American Vertical Datum of 1988, (NAVD88)
Coordinate System: Universal Transverse Mercator (UTM) Zone 11 & 12 North
Units: Horizontal units are in meters to 2 decimal places; Vertical units are in meters to 2 decimal places.
Geoid Model: Geoid18 (used to convert ellipsoid heights to orthometric heights)

Lidar Vertical Accuracy

The tested RMSEz of the classified lidar data for checkpoints in non-vegetated terrain is 6.4 cm, within the 10 cm specification. The NVA of the classified lidar data computed using RMSEz x 1.96 is 12.6 cm, within the 19.6 cm specification.

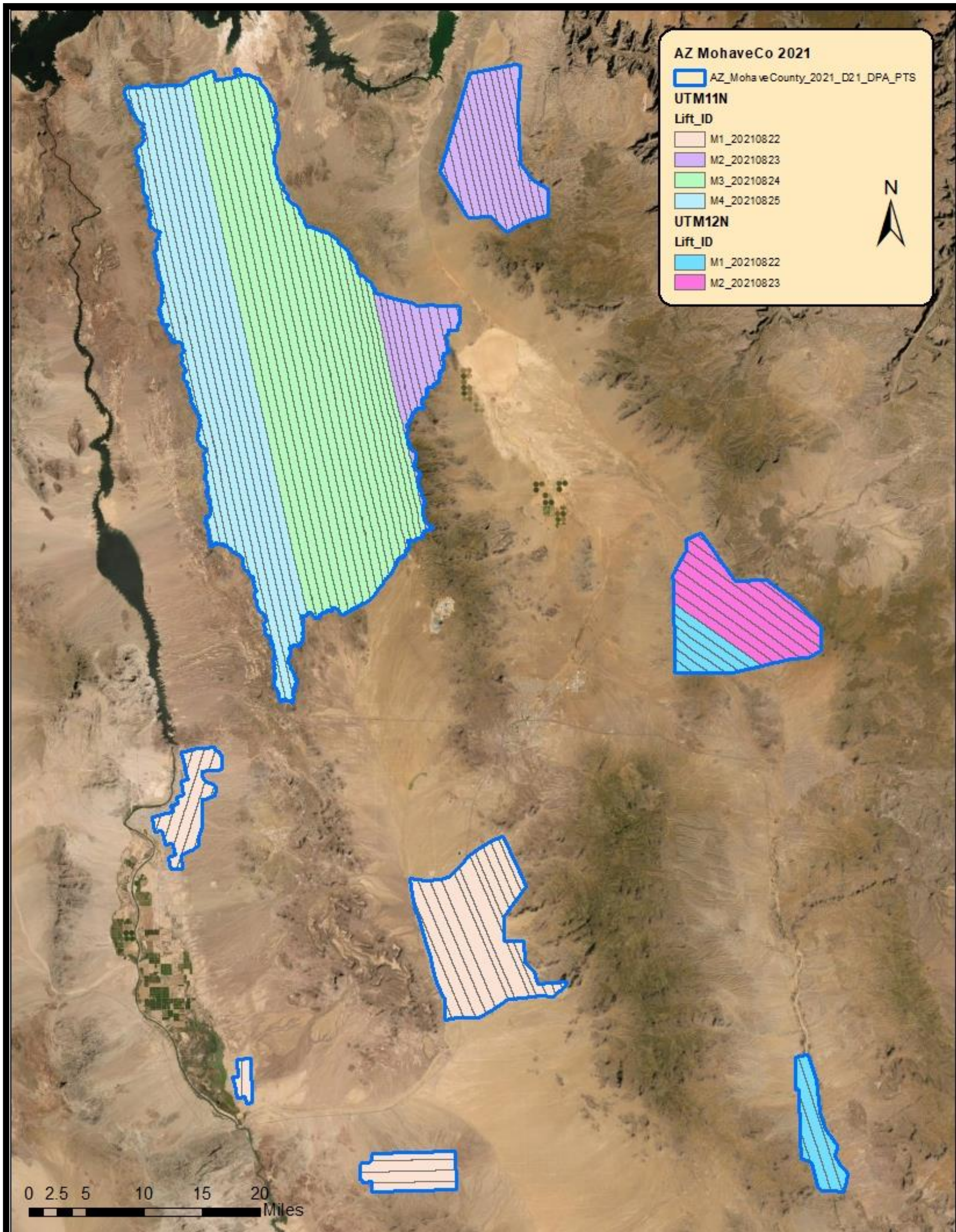
The tested VVA of the classified lidar data computed using the 95th percentile is equal to 13.5 cm, compared to the 30 cm specification.

Project Deliverables

The deliverables for the project are as follows:

1. Classified Point Cloud Data (Tiled)
2. Bare Earth Surface (Raster DEM – GeoTIFF, 32-bit floating-point format)
3. Intensity Images (8-bit gray scale, tiled, GeoTIFF format)
4. Breakline Data (ESRI GDB Feature Class Format)
5. Height Separation Rasters (modulated by intensity)
6. Independent Survey Checkpoint Data (Report, Photos, & Points)
7. Maximum Surface Height Rasters
8. Metadata
9. Project Report (Acquisition, Processing, QC)
10. Project Extents

Project Overview Map



LiDAR Acquisition

Woolpert planned 97 passes for the AZ Mohave project area containing cross ties for the purposes of quality control. To reduce any margin for error in the flight plan, Woolpert followed FEMA's Appendix A "guidelines" for flight planning and, at a minimum, includes the following criteria:

- A digital flight line layout using mission management flight design software for direct integration into the aircraft flight navigation system.
- Planned flight lines; flight line numbers; and coverage area.
- Lidar coverage extended by a predetermined margin (100m) beyond all project borders to ensure necessary over-edge coverage appropriate for specific task order deliverables.
- Local restrictions related to air space and any controlled areas have been investigated so that required permissions can be obtained in a timely manner with respect to schedule. Additionally, Woolpert filed their flight plans as required by local Air Traffic Control (ATC) prior to each mission.

Woolpert monitored weather and atmospheric conditions and conducted lidar missions only when no conditions exist below the sensor that will affect the collection of data. These conditions include leaf-off for hardwoods, no snow, rain, fog, smoke, mist, and low clouds. Lidar systems are active sensors, not requiring light, thus missions may be conducted during night hours when weather restrictions do not prevent collection. Woolpert accesses reliable weather sites and indicators (webcams) to establish the highest probability for successful collection to position our sensor to maximize successful data acquisition.

Within 72-hours prior to the planned day(s) of acquisition, Woolpert closely monitored the weather, checking all sources for forecasts at least twice daily. As soon as weather conditions were conducive to acquisition, our aircraft mobilized to the project site to begin data collection. Once on site, the acquisition team took responsibility for weather analysis.

The lidar survey was conducted between August 22, 2021, and August 25, 2021.

Lidar System Parameters

Woolpert operated a Cessna 404 Titan - N7079F outfitted with a Leica Terrain Mapper LiDAR system during the collection of the study area.

Table 1 lists Woolpert's system parameters for lidar acquisition on this project.

Item	Parameter
System	Leica Terrain Mapper – Serial #90513
Altitude (AGL meters)	2500
Approx. Flight Speed (knots)	150
Scanner Pulse Rate (kHz)	600
Scan Frequency	52
Pulse Duration of the Scanner (nanoseconds)	5
Pulse Width of the Scanner (m)	2.5
Swath width (m)	1820
Central Wavelength of the Sensor Laser (nanometers)	1064
Did the Sensor Operate with Multiple Pulses in The Air? (yes/no)	Yes
Beam Divergence (milliradians)	0.25
Nominal Swath Width on the Ground (m)	1820
Swath Overlap (%)	30
Total Sensor Scan Angle (degree)	40
Nominal Pulse Spacing (single swath), (m)	0.71
Nominal Pulse Density (single swath) (ppsm), (m)	2.0
Aggregate NPS (m) (if ANPS was designed to be met through single coverage, ANPS and NPS will be equal)	0.71
Aggregate NPD (m) (if ANPD was designed to be met through single coverage, ANPD and NPD will be equal)	2.0
Maximum Number of Returns per Pulse	15

Table 1. Woolpert's lidar system parameters.

Acquisition Status Report and Flight Lines

Upon notification to proceed, the flight crew loaded the flight plans and validated the flight parameters. The Acquisition Manager contacted air traffic control and coordinated flight pattern requirements. Lidar acquisition began immediately upon notification that control base stations were in place. During flight operations, the flight crew monitored weather and atmospheric conditions. Lidar missions were flown only when no condition existed below the sensor that would affect the collection of data. The pilot constantly monitored the aircraft course, position, pitch, roll, and yaw of the aircraft. The sensor operator monitored the sensor, the status of PDOPs, and performed the first Q/C review during acquisition. The flight crew constantly reviewed weather and cloud locations. Any flight lines (Figure 1) impacted by unfavorable conditions were marked as invalid and re-flown immediately or at an optimal time.

Figure 1. Trajectories as flown.

Lidar Ground Control

One LiDAR acquisition base station (Table 2) was used to control the lidar acquisition for the AZ Mohave project area. The receiver used during the survey collection, logged at 2 Hertz affixed to a 2-meter range pole served as the base station during acquisition. The coordinates of all used base station positions are provided in Table 2.

Name	NAD83 (2011) UTM 15		Ellipsoidal Ht (m)
	Latitude (N)	Longitude (W)	
NVBM CORS	35 58' 11.31986	115 09' 27.00086	713.237

Table 2. Listing of NGS monuments used for ground control of the lidar data.

Airborne GPS Kinematic and Flightlogs

Inertial Explorer software was used for post-processing of airborne GPS and inertial data (IMU), which is critical to the positioning and orientation of the LiDAR sensor during all flights. Inertial Explorer combines aircraft raw trajectory data with stationary GPS base station data yielding a "Smoothed Best Estimate Trajectory (SBET) necessary for additional post processing software to develop the resulting geo-referenced point cloud from the LiDAR missions.

During the sensor trajectory processing (combining GPS & IMU data sets) certain statistical graphs and tables are generated within the Inertial Explorer processing environment which are commonly used as indicators of processing stability and accuracy. This data for analysis include: Max horizontal / vertical GPS variance, separation plot, altitude plot, PDOP plot, base station baseline length, processing mode, number of satellite vehicles, and mission trajectory.

Flight logs, GPS, and IMU processing reports are included in the Acquisition report: Appendix A.

Generation and Calibration of Laser Points

The initial step of calibration is to verify availability and status of all needed GPS and Laser data against field notes and compile any data if not complete.

Point clouds were then created using Leica HxMap software. The generated point cloud is the mathematical three-dimensional composite of all returns from all laser pulses as determined from the aerial mission. Laser point data are imported into GeoCue, a distributive processing software, which allows for a more manageable file size to be created in a LAS tile format.

On a project level, a supplementary coverage check is carried out to ensure no data voids unreported by Field Operations are present.

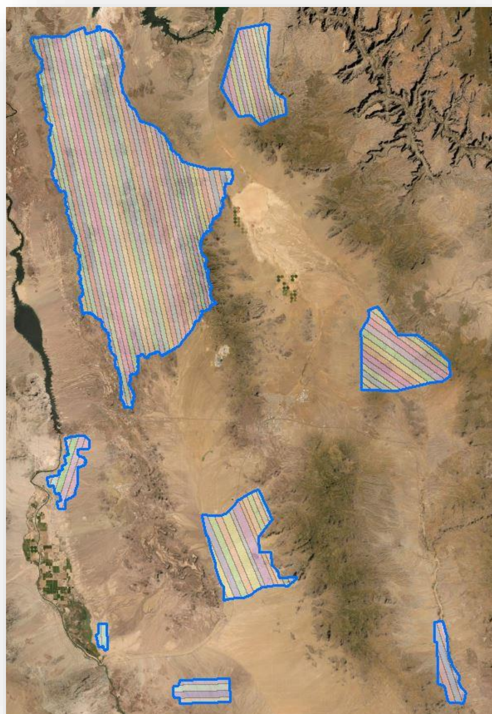


Figure 2. Lidar Swath output showing coverage of Lot Six

Boresight and Relative Accuracy

The initial points for each mission calibration are inspected for flight line errors, flight line overlap, slivers, or gaps in the data, point data minimums, or issues with the lidar unit or GPS. Roll, pitch, and scanner scale are optimized during the calibration process until the relative accuracy is met.

Relative accuracy and internal quality are checked using at least 3 regularly spaced QC blocks in which points from all lines are loaded and inspected. Vertical differences between ground surfaces of each line are displayed. Color scale is adjusted so that errors greater than the specifications are flagged. Cross sections are visually inspected across each block to validate point to point, flight line to flight line and mission to mission agreement. An example of this review is illustrated in Figure 3.

For this project, the specifications used are as follows:
Relative accuracy ≤ 6 cm maximum differences for smooth surface repeatability and ≤8 cm RMSDz between adjacent and overlapping swaths.

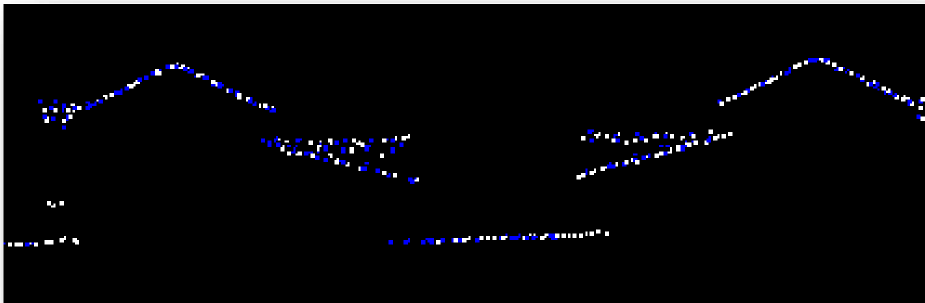


Figure 3. Profile view showing correct roll and pitch adjustments.

Lidar Processing & Quantitative Assessment

Initial Processing

Optimal GEO performed several validations on the dataset prior to starting full-scale production on the project. These validations include vertical accuracy of the swath data, inter-swath (between swath) relative accuracy validation, intra-swath (within a single swath) relative accuracy validation, verification of horizontal alignment between swaths, and confirmation of point density and spatial distribution. This initial assessment allows Optimal GEO to determine if the data are suitable for full-scale production. Addressing issues at this stage allows the data to be corrected while imposing the least disruption possible on the overall production workflow and schedule.

Final Swath Vertical Accuracy Assessment

Optimal GEO tested the vertical accuracy of the non-vegetated terrain swath data prior to additional processing. Vertical accuracy of the swath data was tested using fifty-eight (58) non-vegetated (open terrain and urban) independent survey check points. The vertical accuracy is tested by comparing survey checkpoints in non-vegetated terrain to a triangulated irregular network (TIN) that is created from the raw swath points. Only checkpoints in non-vegetated terrain can be tested against raw swath data because the data has not undergone classification techniques to remove vegetation, buildings, and other artifacts from the ground surface. Checkpoints are always compared to interpolated surfaces from the lidar point cloud because it is unlikely that a survey checkpoint will be located at the location of a discrete lidar point. Optimal GEO utilized MicroStation/TerraScan software to test the classified lidar vertical accuracy, and ESRI's ArcMap to test the DEM vertical accuracy so that two different software programs are used to validate the vertical accuracy for each project. Project specifications require a NVA of 19.6 cm based on the $RMSE_z$ (10 cm) x 1.96.

The dataset for the AZ Mohave LiDAR Project satisfies these criteria. This raw lidar swath data set was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 10 cm $RMSE_z$ Vertical Accuracy Class. Actual NVA accuracy tested to be $RMSE_z$ = 6.6 cm, equating to ± 12.9 cm at 95% confidence level. Table 3 shows all calculated statistics for the raw swath data.

Table 3: NVA at 95% Confidence Level Raw Calibrated Data.

# of Points	RMSE	RMSEz @ 95% CI	Mean (m)	Median (m)	Skew (m)	Std Dev (m)	Min (m)	Max (m)
58	0.066	0.129	0.011	0.014	-0.279	0.065	-0.168	0.162

Inter-Swath Relative Accuracy

Optimal GEO verified inter-swath or between swath relative accuracy of the dataset by creating Delta-Z (DZ) orthomosaics. According to the SOW, USGS Lidar Base Specifications 2020, Revision A, and ASPRS Positional Accuracy Standards for Digital Geospatial Data, 10 cm Vertical Accuracy Class must meet inter-swath relative accuracy of 8 cm RMSDz or less with maximum differences less than 16 cm. These measurements are to be taken in non-vegetated and flat open terrain using last returns.

Measurements are calculated in the DZ orthos on 1-meter pixels or cell sizes. Areas in the dataset where overlapping flight lines are within 8 cm of each other within each pixel are colored green, areas in the dataset where overlapping flight lines have elevation differences in each pixel between 8 cm to 16 cm are colored yellow, and DZ values above 16 cm are red. Pixels that do not contain points from overlapping flight lines are left as no data or black. Areas of vegetation and steep slopes (slopes with 16 cm or more of valid elevation change across 1 linear meter) are expected to appear yellow or red in the DZ orthos. If the project area is heavily vegetated, Optimal GEO may also create DZ Orthos from the initial ground classification only, while keeping all other parameters consistent. This allows Optimal GEO to review the ground classification relative accuracy beneath vegetation and to ensure flight line ridges or other issues do not exist in the final classified data.

Flat, open areas are expected to be green in the DZ orthos. Large or continuous sections of yellow or red pixels can indicate the data was not calibrated correctly or that there were issues during acquisition that could affect the utility of the data, especially when these yellow/red sections follow the flight lines and not the terrain or areas of vegetation. The DZ orthos for the AZ Mohave Lidar Project are shown in Figure 4; this project meets inter-swath relative accuracy specifications.

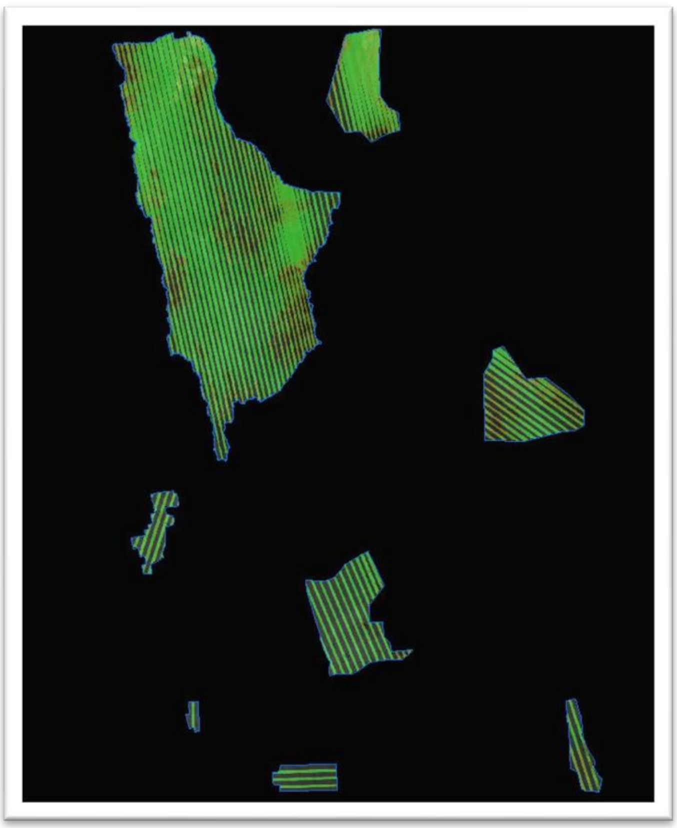


Figure 4. Delta-Z orthoimage raster generated to test inter-swath relative accuracy. Areas in the dataset where overlapping flight lines are within 8 cm of each other within each pixel are colored green, areas in the dataset where overlapping flight lines have elevation differences in each pixel between 8 cm to 16 cm are colored yellow, and DZ values greater than 16cm are colored red. Pixels that do not contain points from overlapping flight lines are left as no data or black. The yellow and red areas in this image are attributed to vegetation or steep slopes.

Intra-Swath Relative Accuracy

Optimal GEO verifies the intra-swath or within swath relative accuracy by LAStools scripting and visual reviews. Scripting is used to calculate the maximum difference of all points within each 1-meter pixel/cell size of each swath. Optimal GEO analysts then identify planar surfaces acceptable for repeatability testing and analysts review the results in those areas. According to the SOW, USGS Lidar Base Specifications v2.1, and ASPRS Positional Accuracy Standards for Digital Geospatial Data, 10 cm Vertical Accuracy Class must meet intra-swath relative accuracy of 6 cm maximum difference or less. Figure 5 shows examples of the intra-swath relative accuracy of the AZ Mohave QL2 lidar data; this project meets intra-swath relative accuracy specifications.

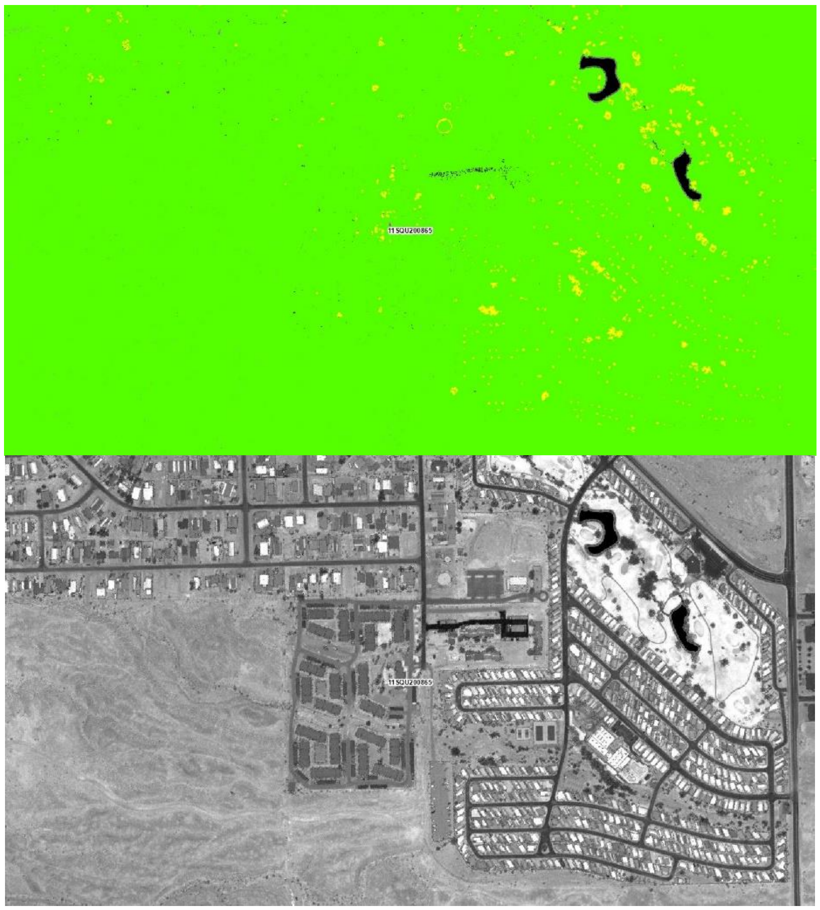


Figure 5. Intra-swath relative accuracy. The top image shows a close up of the project area; flat, open areas are colored green as they are within 6 cm whereas sloped terrain is colored yellow because it exceeds 6 cm maximum difference, as expected, due to actual slope/terrain change. The bottom image is a close-up of a flat area. Except for vegetated areas and around buildings (shown as yellow speckling/mottling as the elevation/height difference in vegetated areas will exceed 6 cm), this open flat area is acceptable for repeatability testing. Intra-swath relative accuracy passes specifications.

Horizontal Alignment

To ensure horizontal alignment between adjacent or overlapping flight lines, Optimal GEO uses LAStools scripting and visual reviews. LAStools scripting is used to create files similar to DZ orthos for each swath but this process highlights planar surfaces, such as roof tops. Horizontal shifts or misalignments between swaths on roof tops and other elevated planar surfaces are highlighted. Visual reviews of these features, including additional profile verifications, are used to confirm the results of this process. Figure 6 shows an example of the horizontal alignment between swaths.

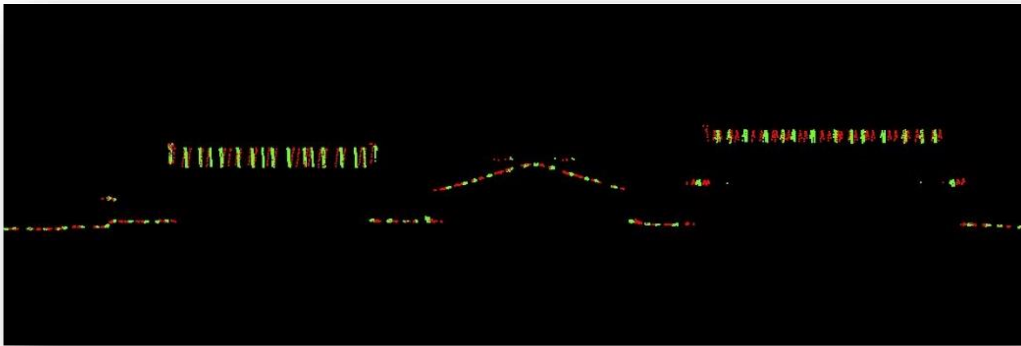


Figure 6. Profile of a lidar point cloud cross section of a buildings. Points are colorized by flight line number.

Point Density and Spatial Distribution

The required Aggregate Nominal Point Spacing (ANPS) for this project is no greater than 0.71 meters, which equates to an Aggregate Nominal Point Density (ANPD) of 2 points per square meter (ppsm) or greater for the QL2 area. Density calculations were performed using first return data only located in the geometrically usable center portion (typically ~90%) of each swath. By utilizing statistics, it was determined that the project meets the required ANPS and ANPD specifications for the QL2 area.

The spatial distribution of points must be uniform and free of clustering. This specification is tested by creating a grid with cell sizes equal to the design NPS*2. LAStools scripting is then used to calculate the number of first return points of each swath within each grid cell. At least 90% of the cells must contain 1 lidar point, excluding acceptable void areas such as water or low NIR reflectivity features, i.e. some asphalt and roof composition materials.

To perform this test, Optimal GEO generated a Spatial Distribution raster grid from first return lidar points. This grid was generated for all tiles that intersect the project area. Optimal GEO did not identify any tiles where less than 90% of the cells did not contain at least one lidar point excluding acceptable void areas. Figure 7 below illustrates the spatial distribution.

Optimal GEO did identify voids in the lidar data that were larger than USGS' tolerance for acceptable data voids as defined in the task order. According to the USGS Lidar Base Specification, data voids are gaps in point cloud coverage greater or equal to $(4*ANPS)^2$ measured using only first returns within a single swath. The voids were identified using a density raster. Each void identified was assessed against the latest imagery in Google Earth. The types of voids found in the dataset occurred from water bodies, rock formations, or in areas of low reflectance.

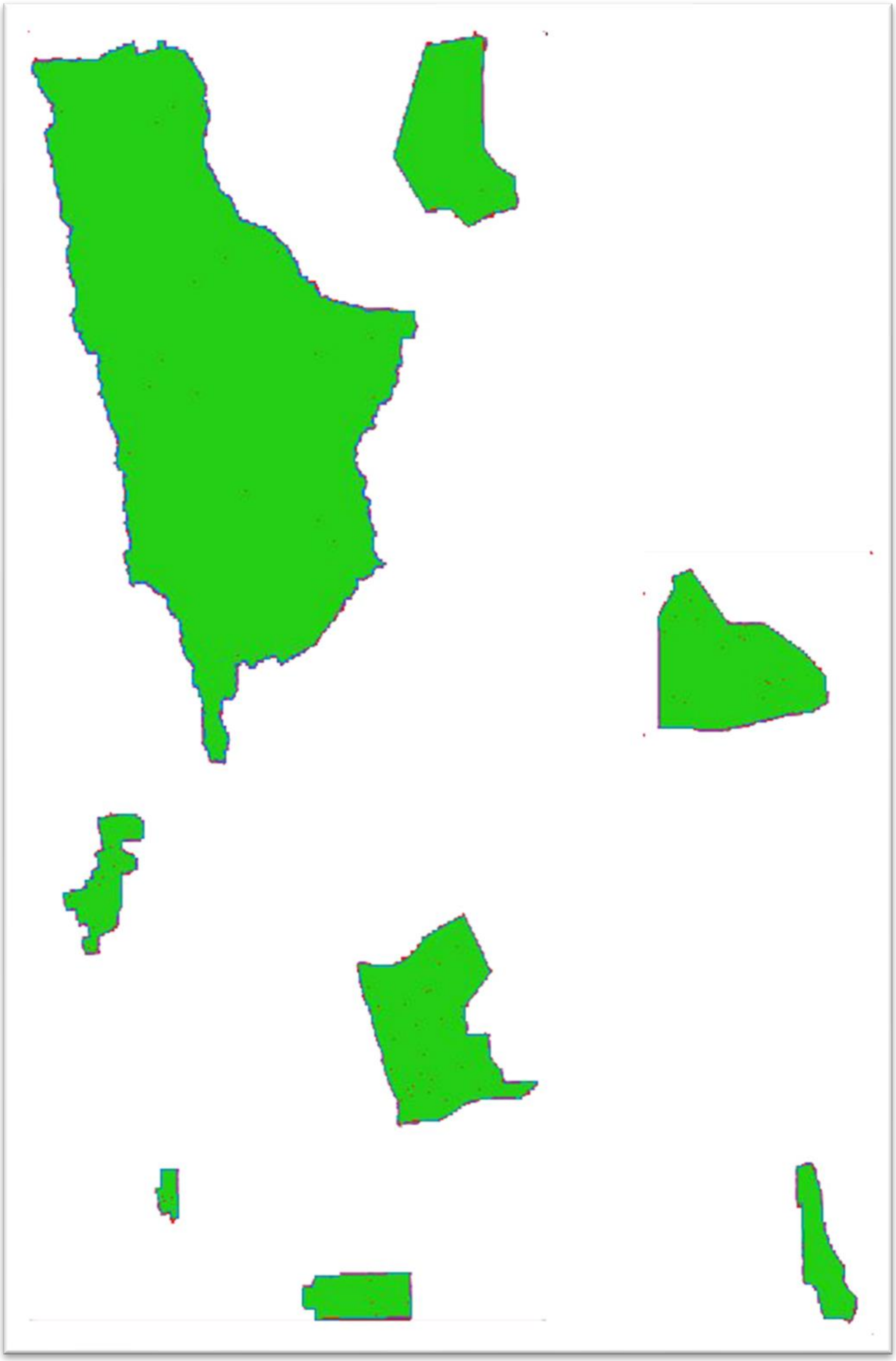


Figure 7. Spatial distribution raster generated from first return lidar pulses of the lidar data. Green pixels are areas with a count of 1 point or greater. Red pixels contain no data. The red areas are attributed to small ponds or variations in aircraft pitch that occurred during the acquisition.

Data Classification and Editing

Once the calibration, absolute swath vertical accuracy, and relative accuracy of the data was confirmed, Optimal GEO utilized a variety of software suites for data processing. The data was processed using TerraScan software. The initial step is the setup of the TerraScan project, which is done by importing a project defined tile boundary index encompassing the entire project area. The acquired 3D laser point clouds, in LAS binary format, were imported into the TerraScan project and tiled according to the project tile grid. Once tiled, the laser points were classified using a proprietary routine in TerraScan. This routine classifies any obvious low outliers in the dataset to class 7 and high outliers in the dataset to class 18. Points along flight line edges that are geometrically unusable are identified as withheld and classified to a separate class so that they will not be used in the initial ground algorithm. After points that could negatively affect the ground are removed from class 1, the ground layer is extracted from this remaining point cloud. The ground extraction process encompassed in this routine takes place by building an iterative surface model.

This surface model is generated using three main parameters: building size, iteration angle and iteration distance. The initial model is based on low points being selected by a "roaming window" with the assumption that these are the ground points. The size of this roaming window is determined by the building size parameter. The low points are triangulated, and the remaining points are evaluated and subsequently added to the model if they meet the iteration angle and distance constraints. This process is repeated until no additional points are added within iterations. A second critical parameter is the maximum terrain angle constraint, which determines the maximum terrain angle allowed within the classification model.

Each tile was then imported into TerraScan, and a surface model was created to examine the ground classification. Optimal GEO analysts visually reviewed the ground surface model and corrected errors in the ground classification such as vegetation, buildings, and bridges that were present. Optimal GEO analysts employ 3D visualization techniques to view the point cloud at multiple angles and in profile to ensure that non-ground points are removed from the ground classification. After the ground classification corrections were completed, the dataset was processed through a water classification routine that utilizes breaklines compiled to automatically classify hydro features. The water classification routine selects ground points within the breakline polygons and automatically classifies them as class 9, water. During this water classification routine, points that are within 0.30 meters of the hydrographic features are moved to class 20, an ignored ground due to breakline proximity. Overage points are then identified and used in TerraScan to set the overlap bit for the overage points and the withheld bit is set on the withheld points previously identified before theground classification routine was performed.

The lidar tiles were classified to the following classification schema:

- Class 1 = Unclassified, used for all other features that do not fit into the Classes 2, 7, 9, 17, 18, 20, 21, or 22, including vegetation, buildings, etc.
- Class 2 = Bare-Earth Ground
- Class 7 = Low Noise
- Class 9 = Water, points located within collected breaklines
- Class 17 = Bridge Decks
- Class 18 = High Noise
- Class 20 = Ignored Ground due to breakline proximity
- Class 21 = Snow
- Class 22 = Temporal Exclusion

After manual classification, the LAS tiles were peer reviewed and then underwent a final QA/QC. After the final QA/QC and corrections, all headers, appropriate point data records, and variable length records, including spatial reference information, are updated in TerraScan software, and then verified using proprietary Optimal GEO tools.

Lidar Qualitative Assessment

Optimal GEO's qualitative assessment utilizes a combination of statistical analysis and interpretative methodology or visualization to assess the quality of the data for a bare-earth digital terrain model (DTM). This includes creating pseudo image products such as lidar orthos produced from the intensity returns, Triangular Irregular Network (TIN)'s, Digital Elevation Models (DEM) and 3-dimensional models as well as reviewing the actual point cloud data. This process looks for anomalies in the data, areas where man-made structures or vegetation points may not have been classified properly to produce a bare-earth model, and other classification errors. This report will present representative examples where the lidar and post processing had issues as well as examples of where the lidar performed well.

Formatting

After the final QA/QC is performed and all corrections have been applied to the dataset, all lidar files are updated to the final format requirements and the final formatting, header information, point data records, and variable length records are verified using Optimal GEO's proprietary tools. Table 4 lists some of the main lidar header fields that are updated and verified.

Classified Lidar Formatting		
Parameter	**Requirement**	**Pass/Fail**
LAS Version	1.4	Pass
Point Data Format	Format 6	Pass
Coordinate Reference System	NAD83 (2011) Universal Transverse Mercator (UTM) Zone 11 & 12 North, meters and NAVD88 (Geoid 18), meters in WKT Format	Pass
Global Encoder Bit	Should be set to 17 for Adjusted GPS Time	Pass
Time Stamp	Adjusted GPS Time (unique timestamps)	Pass
System ID	Should be set to the processing system/software and is set to TerraScan	Pass
Multiple Returns	The sensor shall be able to collect multiple returns per pulse and the return numbers are recorded	Pass
Intensity	16-bit intensity values are recorded for each pulse	Pass
Classification	Required Classes include: Class 1: Unclassified Class 2: Ground Class 7: Low Noise Class 9: Water Class 17: Bridge Decks Class 18: High Noise Class 20: Ignored Ground Class 21: Snow Class 22: Temporal Exclusion	Pass, class 21 and 22 were not utilized
Withheld Points	Noise points are set with the Withheld bits	Pass
Scan Angle	Recorded for each pulse	Pass
XYZ Coordinates	Unique Easting, Northing, and Elevation coordinates are recorded for each pulse	Pass

Table 4. Classified Lidar Formatting.

Lidar Positional Accuracy

Background

Optimal GEO quantitatively tested the dataset by testing the vertical accuracy of the lidar. The vertical accuracy is tested by comparing the discreet measurement of the survey checkpoints to that of the interpolated value within the three closest lidar points that constitute the vertices of a three-dimensional triangular face of the TIN. Therefore, the result is that only a small sample of the lidar data is actually tested. However, there is an increased level of confidence with lidar data due to the relative accuracy. This relative accuracy in turn is based on how well one lidar point "fits" in comparison to the next contiguous lidar measurement and is verified as part of the initial processing. If the relative accuracy of a dataset is within specifications and the dataset passes vertical accuracy requirements at the location of survey checkpoints, the vertical accuracy results can be applied to the whole dataset with high confidence due to the passing relative accuracy. Typically, TerraScan software to test the classified lidar vertical accuracy, and ESRI ArcMap to test the DEM vertical accuracy so that two different software programs are used to validate the vertical accuracy for each project.

Survey Vertical Accuracy Checkpoints

For the final vertical accuracy assessment, one hundred and five (105) check points were utilized for the project and are located within bare earth/open terrain, grass/weeds/crops, or forested/fully grown land cover categories. Please see the included survey report found in the survey folder of the deliverables structure which details and validates how the survey was completed for this project.

Checkpoints were evenly distributed throughout the project area to cover as many flight lines as possible using the “dispersed method” of placement.

Table 5 lists the location of the QA/QC checkpoints used to test the positional accuracy of the dataset.

Table 5. Ground Surveyed Vertical Accuracy Check Points.

Point ID	UTM Zone	NAD83(2011)		Elevation (m; NAVD88 Geoid18)
		Easting X (m)	Northing Y (m)	
2001_h_2021_AZ	11N	723811.993	3884541.6	322.494
2002_2021_AZ	11N	749152.611	3836757.832	488.501
2003_2021_AZ	11N	756143.961	3878534.549	662.897
2006_2021_AZ	12N	262268.865	3840606.002	597.681
2007_2021_AZ	11N	734567.062	3939125.342	864.479
2008_2021_AZ	11N	743074.369	3958499.751	1169.358
2009_2021_AZ	11N	741416.871	3957291.128	1097.482
2010_2021_AZ	11N	750074.579	3919819.826	1087.709
2011_2021_AZ	11N	761812.923	3881285.477	750.257
2012_2021_AZ	11N	767278.834	3862546.589	699.201
2013_2021_AZ	11N	747011.041	3941260.191	1028.878
2015_2021_AZ	11N	748832.796	3948364.793	1092.971
2016_2021_AZ	11N	755752.326	3949363.222	1071.022
2018_2021_AZ	11N	763340.633	3978071.431	1129.805
2021_2021_AZ	11N	765190.943	3976912.512	1151.536
2022_2021_AZ	11N	764896.039	3973412.476	1249.978
2024_2021_AZ	11N	724762.836	3977307.643	551.999

Table 5. Ground Surveyed Vertical Accuracy Check Points continued.

2025_2021_AZ	11N	747989.128	3935333.779	1045.419
2026_2021_AZ	12N	260746.043	3847493.458	615.136
2027_2021_AZ	11N	732572.385	3958276.629	793.716
2028_2021_AZ	11N	748176.326	3921704.097	1080.371
2029_2021_AZ	11N	764346.774	3984795.602	977.4
2034_2021_AZ	12N	253632.762	3915632.716	1130.404
2035_2021_AZ	11N	740033.748	3941685.409	885.979
2036_2021_AZ	11N	768485.795	3975922.622	1211.18
2038_h_2021_AZ	11N	722720.509	3888023.637	278.456
2039_2021_AZ	11N	761575.629	3866385.914	610.698
2040_2021_AZ	12N	253986.217	3916920.729	1110.658
2041_2021_AZ	11N	742148.448	3931569.411	948.538
2042_2021_AZ	11N	752638.027	3948466.794	1084.47
2043_2021_AZ	11N	747205.744	3934281.143	1037.11
2044_h_2021_AZ	11N	722766.507	3894467.191	207.493
2045_2021_AZ	11N	736760.114	3933476.525	896.186
2048_2021_AZ	11N	761370.065	3876932.145	707.589
2050_2021_AZ	11N	741108.875	3943505.111	921.51
2052_2021_AZ	11N	742503.511	3939333.338	924.775
2054_2021_AZ	11N	744692.344	3933754.88	987.148
2055_H_2021_AZ	11N	740940.286	3957559.345	1080.58
2056_H_2021_AZ	11N	748925.787	3945884.264	1092.683
2059_H_2021_AZ	11N	738165.982	3938133.14	869.555
2060_2021_AZ	11N	752171.08	3837283.233	529.816
2061_2021_AZ	12N	260570.587	3844844.521	617.035
2063_2021_AZ	11N	730389.417	3850937.232	190.969
2064_2021_AZ	11N	737042.216	3940086.275	849.755
2065_2021_AZ	11N	751442.225	3838596.149	484.518
2068_2021_AZ	11N	730513.853	3852417.73	197.402
2069_2021_AZ	11N	751485.856	3921730.915	1149.052
2070_2021_AZ	11N	745830.616	3925448.418	1053.075
2071_2021_AZ	11N	738844.531	3922510.26	992.334
2072_2021_AZ	11N	732247.538	3931155.235	986.008
2073_2021_AZ	11N	727291.488	3956205.94	737.343
2074_2021_AZ	11N	725692.57	3979859.561	514.006
2075_2021_AZ	11N	725153.522	3984898.932	524.092
2076_2021_AZ	11N	724092.982	3974213.257	578.645
2077_2021_AZ	11N	723204.555	3971279.708	613.26
2078_2021_AZ	11N	721777.693	3965909.755	699.828
2079_2021_AZ	11N	735147.132	3943204.883	823.893

Table 5. Ground Surveyed Vertical Accuracy Check Points continued.

2080_2021_AZ	11N	735093.664	3933494.932	916.625
3001_2021_AZ	11N	725299.711	3891014.957	359.56
3002_2021_AZ	11N	744375.895	3935161.943	972.922
3003_2021_AZ	11N	765173.466	3977682.33	1137.128
3004_2021_AZ	11N	747656.713	3940310.413	1071.819
3005_2021_AZ	11N	751841.47	3922588.495	1180.326
3006_2021_AZ	11N	749193.581	3920129.103	1077.447
3007_2021_AZ	11N	769598.469	3866005.393	819.939
3008_2021_AZ	11N	739826.211	3929855.836	917.799
3009_2021_AZ	11N	738971.52	3927363.538	932.379
3010_2021_AZ	11N	735924.756	3924033.084	969.352
3011_2021_AZ	11N	749600.72	3949716.221	1094.285
3013_2021_AZ	11N	735471.407	3931590.371	927.748
3015_2021_AZ	11N	746831.366	3947239.092	1136.658
3016_2021_AZ	11N	756227.307	3958215.712	980.136
3017_2021_AZ	11N	761509.218	3865643.62	602.998
3019_2021_AZ	11N	741881.367	3942385.509	928.905
3020_2021_AZ	11N	730717.032	3848844.721	159.69
3021_2021_AZ	11N	762981.816	3984922.135	996.814
3022_2021_AZ	11N	747896.978	3944570.518	1073.204
3024_2021_AZ	11N	747720.044	3938268.095	1056.852
3025_2021_AZ	11N	740849.328	3956220.244	1056.655
3026_2021_AZ	11N	736863.437	3966284.629	1005.676
3027_2021_AZ	11N	763376.801	3971346.848	1172.841
3028_2021_AZ	11N	749151.802	3837350.067	474.758
3029_2021_AZ	11N	726127.758	3952458.666	793.369
3030_2021_AZ	11N	736468.002	3975749.006	834.165
3032_2021_AZ	12N	263992.079	3837197.201	554.505
3034_2021_AZ	12N	258427.359	3908217.128	1204.348
3035_2021_AZ	11N	730614.129	3959241.675	753.649
3036_2021_AZ	11N	745296.74	3938432.081	985.911
3038_2021_AZ	11N	748042.799	3945028.365	1076.643
3039_2021_AZ	11N	763575.682	3868075.829	649.136
3040_2021_AZ	12N	261409.867	3841932.864	596.768
3041_2021_AZ	11N	748407.091	3949563.384	1107.996
3042_2021_AZ	12N	245510.177	3911977.749	1348.975
3045_2021_AZ	11N	733987.796	3939316.788	875.392
3047_2021_AZ	11N	749830.902	3949014.562	1079.861
3048_2021_AZ	11N	751069.846	3839010.823	469.155
3050_2021_AZ	11N	740975.63	3935243.458	919.26

Table 5. Ground Surveyed Vertical Accuracy Check Points continued.

3051_2021_AZ	11N	752055.886	3949664.148	1054.394
3052_2021_AZ	11N	726184.015	3894510.5	378.654
3054_2021_AZ	11N	756010.145	3927574.796	1680.632
3055_2021_AZ	11N	738303.306	3966360.063	1057.939
3056_2021_AZ	11N	739829.876	3959382.171	1074.274
3057_2021_AZ	11N	736421.226	3974740.259	863.107
3058_2021_AZ	11N	723337.811	3971546.849	607.388
3059_2021_AZ	11N	724144.466	3974304.004	575.881

Vertical Accuracy Test Procedures

Non-vegetated Vertical Accuracy

NVA (Non-vegetated Vertical Accuracy) is determined with check points located only in non-vegetated terrain, including open terrain (grass, dirt, sand, and/or rocks) and urban areas, where there is a very high probability that the lidar sensor will have detected the bare-earth ground surface and where random errors are expected to follow a normal error distribution. The NVA determines how well the calibrated lidar sensor performed. With a normal error distribution, the vertical accuracy at the 95% confidence level is computed as the vertical root mean square error (RMSEz) of the checkpoints x 1.9600. For the AZ Mohave Lidar Project, vertical accuracy must be 19.6 cm or less based on an RMSEz of 10 cm x 1.9600.

Vegetated Vertical Accuracy

VVA (Vegetated Vertical Accuracy) is determined with all checkpoints in vegetated land cover categories, including tall grass, weeds, crops, brush and low trees, and fully forested areas, where there is a possibility that the lidar sensor and post-processing may yield elevation errors that do not follow a normal error distribution. VVA at the 95% confidence level equals the 95th percentile error for all checkpoints in all vegetated land cover categories combined. The AZ Mohave lidar project VVA standard is 30 cm based on the 95th percentile. Here, $Accuracy_z$ differs from VVA because $Accuracy_z$ assumes elevation errors follow a normal error distribution where RMSE procedures are valid, whereas VVA assumes lidar errors may not follow a normal error distribution in vegetated categories, making the RMSE process invalid. The relevant testing criteria are summarized in Table 6.

Quantitative Criteria	Measure of Acceptability
Non-Vegetated Vertical Accuracy (NVA) in open terrain and urban land cover categories using $RMSE_z$ *1.9600	19.6 cm (based on $RMSE_z$ (10 cm) * 1.9600)
Vegetated Vertical Accuracy (VVA) in all vegetated land cover categories combined at the 95% confidence level	30 cm (based on 95th percentile)

Table 6. Acceptance Criteria

The primary QA/QC vertical accuracy testing steps used by Optimal GEO are summarized as follows:

1. The ground team surveyed QA/QC vertical checkpoints in accordance with the project's specifications.
2. Next, Optimal GEO interpolated the bare-earth lidar TIN to provide the z-value for everycheckpoint.
3. Optimal GEO then computed the associated z-value differences between the interpolated z-value from the lidar data and the ground truth survey checkpoints and computed NVA, VVA, and other statistics.
4. The data were analyzed by Optimal GEO to assess the accuracy of the data. The review process examined the various accuracy parameters as defined by the scope of work. The overall descriptive statistics of each dataset were computed to assess any trends or anomalies. This report provides tables, graphs, and figures to summarize and illustrate data quality.

Vertical Accuracy Results

Table 7 summarizes the tested vertical accuracy resulting from a comparison of the surveyed checkpoints to the elevation values present within the fully classified lidar LAS files.

Land Cover Category	# of Points	NVA — Non-vegetated Vertical Accuracy ($RMSE_z$ x 1.9600) Spec=19.6 cm	VVA — Vegetated Vertical Accuracy (95th Percentile) Spec=29.4 cm NVA
NVA	58	12.6 cm	
VVA	47		13.5 cm

Table 7. Tested NVA and VVA

This lidar dataset was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 10 cm RMSEz Vertical Accuracy Class. Actual NVA accuracy was found to be $RMSE_z$ =6.4 cm, equating to ± 12.6 cm at 95% confidence level. Actual VVA accuracy was found to be ± 13.5 cm at the 95th Percentile.

Table 8 provides overall descriptive statistics.

100 % of Totals	# of Points	RMSEz (m) @95% CL	Mean (m)	Median (m)	Skew	Std Dev (m)	Min (m)	Max (m)
NVA	58	0.126	0.004	0.011	-0.208	0.064	-0.168	0.142
VVA	47	N/A	0.005	0.011	-0.032	0.065	-0.158	0.223

Table 8. Overall Descriptive Statistics

Based on the vertical accuracy testing conducted by Optimal GEO, the lidar dataset for the AZ Mohave Lidar Project QL2 Delivery satisfies the project's pre-defined vertical accuracy criteria.

Breakline Production & Qualitative Assessment Report

Breakline Production Methodology

Optimal GEO digitized the project's hydrographic breaklines from the lidar utilizing the TIN and intensity for visualization and placement. This technique enables Optimal GEO to produce accurate 3D hydrographic breaklines for features that are consistent with the lidar data at the time of airborne survey. All drainage breaklines are monotonically enforced to show downhill flow. Water bodies are at a constant elevation where the water body has been captured at the lowest elevation. Bridge deck breaklines are compiled directly from the project's DEMs. Bridge Breaklines are used where necessary to show the logical flow of the terrain beneath bridge decks and to prevent bridge saddles in the bare earth DEMs. All features were compiled in accordance with the project's Data Dictionary.

Breakline Qualitative Assessment

Completeness and horizontal placement are verified through visual reviews against lidar intensity imagery. Automated checks are applied on all breakline features to validate topology, including the 3D connectivity of features, enforced monotonicity on linear hydrographic breaklines, and flatness on water bodies. After all corrections and edits to the breakline features, the breaklines are imported into the final GDB and verified for correct formatting.

Breakline Data Dictionary

The following data dictionary was used for this project.

Horizontal and Vertical Datum

The horizontal datum shall be North American Datum of 1983, 2011 adjustment (NAD83 2011), Units in Meters. The vertical datum shall be referenced to the North American Vertical Datum of 1988, Units in Meters. Geoid18 shall be used to convert ellipsoidal heights to orthometric heights.

Coordinate System and Projection

All data shall either be projected to Universal Transverse Mercator (UTM) Zone 11 & 12 North, Horizontal Units in Meters and Vertical Units in Meters.

Inland Streams and Rivers

Feature Class: BREAKLINES
Feature Type: Polyline
Contains Z Values: Yes
XY Resolution: Accept Default Setting
XY Tolerance: 0.003

Contains M Values: No
Annotation Subclass: None
Z Resolution: Accept Default Setting
Z Tolerance: 0.001

Description

This polygon feature class will depict linear hydrographic features with a width greater than 100 feet.

Table Definition

Field Name	Data Type	Allow Null Values	Default Value	Domain	Precision	Scale	Length	Responsibility
OBJECTID	Object ID							Assigned by Software
SHAPE	Geometry							Assigned by Software
SHAPE_LENGTH	Double	Yes			0	0		Calculated by Software
Type	String	Yes			0	0	25	Assigned by Analyst

Feature Definition

Description	Definition	Capture Rules
Streams and Rivers	Linear hydrographic features such as streams, rivers, canals, etc. with an average width greater than 100 feet. In the case of embankments, if the feature forms a natural dual line channel, then capture it consistent with the capture rules. Other natural or manmade embankments will not qualify for this project.	Capture features showing dual line (one on each side of the feature). Average width shall be greater than 100 feet to show as a double line. Each vertex placed should maintain vertical integrity. Generally, both banks shall be collected to show consistent downhill flow. There are exceptions to this rule where a small branch or offshoot of the stream or river is present. The banks of the stream must be captured at the same elevation to ensure flatness of the water feature. If the elevation of the banks appears to be different see the task manager or PM for further guidance. Breaklines must be captured at or just below the elevations of the immediately surrounding terrain. Under no circumstances should a feature be elevated above the surrounding lidar points. Acceptable variance in the negative direction will be defined for each project individually. These instructions are only for docks or piers that follow the coastline or water's edge, not for docks or piers that extend perpendicular from the land into the water. If it can be reasonably determined where the edge of water most probably falls, beneath the dock or pier, then the edge of water will be collected at the elevation of the water where it can be directly measured. If there is a clearly-indicated headwall or bulkhead adjacent to the dock or pier and it is evident that the waterline is most probably adjacent to the headwall or bulkhead, then the water line will follow the headwall or bulkhead at the elevation of the water where it can be directly measured. If there is no clear indication of the location of the water's edge beneath the dock or pier, then the edge of water will follow the outer edge of the dock or pier as it is adjacent to the water, at the measured elevation of the water. Every effort should be made to avoid breaking a stream or river into segments. Dual line features shall break at road crossings (culverts). In areas where a bridge is present the dual line feature shall continue through the bridge. Islands: The double line stream shall be captured around an island if the island is greater than 1 acre. In this case a segmented polygon shall be used around the island to allow for the island feature to remain as a "hole" in the feature.

Inland Ponds and Lakes

Feature Class: BREAKLINES
Feature Type: Polygon
Contains Z Values: Yes
XY Resolution: Accept Default Setting
XY Tolerance: 0.003
Contains M Values: No
Annotation Subclass: None
Z Resolution: Accept Default Setting
Z Tolerance: 0.001

Description

This polygon feature class will depict closed water body features that are at a constant elevation.

Table Definition

Field Name	Data Type	Allow Null Values	Default Value	Domain	Precision	Scale	Length	Responsibility
OBJECTID	Object ID							Assigned by Software
SHAPE	Geometry							Assigned by Software
SHAPE_LENGTH	Double	Yes			0	0		Calculated by Software
TYPE	String	Yes					25	Assigned by Analyst
SHAPE_AREA	Double	Yes			0	0		Calculated by Software

Feature Definition

Description	Definition	Capture Rules
Ponds and Lakes	Land/Water boundaries of constant elevation water bodies such as lakes, reservoirs, ponds, etc. Features shall be defined as closed polygons and contain an elevation value that reflects the best estimate of the water elevation at the time of data capture. Water body features will be captured for features 2 acres in size or greater. "Donuts" will exist where there are islands within a closed water body feature.	Water bodies shall be captured as closed polygons with the water feature to the right. The compiler shall take care to ensure that the z-value remains consistent for all vertices placed on the water body. Breaklines must be captured at or just below the elevations of the immediately surrounding terrain. Under no circumstances should a feature be elevated above the surrounding lidar points. Acceptable variance in the negative direction will be defined for each project individually. An Island within a Closed Water Body Feature that is 1 acre in size or greater will also have a "donut polygon" compiled. These instructions are only for docks or piers that follow the coastline or water's edge, not for docks or piers that extend perpendicular from the land into the water. If it can be reasonably determined where the edge of water most probably falls, beneath the dock or pier, then the edge of water will be collected at the elevation of the water where it can be directly measured. If there is a clearly-indicated headwall or bulkhead adjacent to the dock or pier and it is evident that the waterline is most probably adjacent to the headwall or bulkhead, then the water line will follow the headwall or bulkhead at the elevation of the water where it can be directly measured. If there is no clear indication of the location of the water's edge beneath the dock or pier, then the edge of water will follow the outer edge of the dock or pier as it is adjacent to the water, at the measured elevation of the water.

DEM Production & Qualitative Assessment

DEM Production Methodology

Optimal GEO generates a DEM from a TIN using points and breaklines utilizing a combination of TerraSolid (v21) and GDAL (2.4.0) software packages. Once the DEM is created, it is reviewed in ArcGIS for any issues requiring corrections, including remaining lidar misclassifications, erroneous breakline elevations, poor hydro-flattening or hydro-enforcement, and processing artifacts. After corrections are applied, the DEM is then split into individual tiles in accordance with the project tiling scheme. The tiles are verified for final formatting and then loaded into Global Mapper to ensure no missing or corrupt tiles and to ensure seamlessness across tile boundaries.

DEM Qualitative Assessment

Optimal GEO performed a comprehensive qualitative assessment of the bare earth DEM deliverables to ensure that all tiled DEM products were delivered with the proper extents, were free of processing artifacts, and contained the proper referencing information. This process was performed in ArcGIS software with the use of a tool set Optimal GEO has developed to verify that the raster extents match those of the tile grid and contain the correct projection information. The DEM data was reviewed at a scale of 1:5000 to review for artifacts caused by the DEM generation process and to review the hydro-flattened features. To perform this review Optimal GEO creates hillshade models and overlays a partially transparent colorized elevation model to review for these issues. All corrections are completed using

Optimal GEO's proprietary correction workflow. Upon completion of the corrections, the DEM data is loaded into Global Mapper for its second review and to verify corrections. Once the DEMs are tiled out, the final tiles are again loaded into Global Mapper to ensure coverage, extents, and that the final tiles are seamless.

DEM Vertical Accuracy Results

One hundred and five (105) checkpoints that were used to test the vertical accuracy of the lidar were used to validate the vertical accuracy of the final DEM products. Accuracy results may vary between the source lidar and final DEM deliverable. DEMs are created by taking a sample of the TIN at the center of each pixel which may result in slightly different elevation values at each survey checkpoint when compared to the source LAS, which does not average several lidar points together but may interpolate (linearly) between three points to derive an elevation value. The vertical accuracy of the DEM is tested by extracting the elevation of the pixel that contains the x/y coordinates of the checkpoint and comparing these DEM elevations to the surveyed elevations. Optimal GEO typically uses TerraScan software to test the swath lidar vertical accuracy, to test the classified lidar vertical accuracy, and ESRI ArcMap to test the DEM vertical accuracy so that two different software programs are used to validate the vertical accuracy for each project.

Table 10 summarizes the tested vertical accuracy results from a comparison of the surveyed checkpoints to the elevation values present within the final DEM dataset.

Land Cover Category	# of Points	NVA — Non-vegetated Vertical Accuracy ($RMSE_z$ x 1.9600) Spec=19.6 cm	VVA — Vegetated Vertical Accuracy (95th Percentile) Spec=30 cm
NVA	58	12.2 cm	
VVA	47		14.7 cm

Table 10. DEM tested NVA and VVA

This DEM dataset was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 10 cm RMSEz Vertical Accuracy Class. Actual NVA accuracy was found to be $RMSE_z$ = 6.2 cm, equating to +/- 12.2 cm at 95% confidence level. Actual VVA accuracy was found to be +/- 14.7 cm at the 95th percentile.

Table 11 provides overall descriptive statistics.

100 % of Totals	# of Points	RMSEz (m) @95% CL	Mean (m)	Median (m)	Skew	Std Dev (m)	Min (m)	Max (m)
NVA	58	0.122	0.003	0.005	-0.175	0.062	-0.158	0.149
VVA	47	N/A	0.005	0.006	-0.135	0.067	-0.168	0.223

Table 11. Overall Descriptive Statistics

Based on the vertical accuracy testing conducted by Optimal GEO, the DEM dataset for the AZ Mohave Lidar Project QL2 Delivery satisfies the project's pre-defined vertical accuracy criteria.

Appendix A: Flightlogs, IMU, and GPS Processing Reports

Mission 1 (20210822)

Flight Log

Woolpert Lidar Acquisition Log

Project Info			Date		
Project #	Project Name	Unique ID	Flight Date (UTC)	Day of Year	Flight #
82345	NW AZ Mojave	Day234_90513	08/22/2021	234	

Crew	Equipment	Time			Airports
Pilot	Aircraft Make / Model / Tail #	Hobbs Start	Local Start	UTC Start	Departing
Connolly	Cessna 404 Titan - N7079F	3189.9	07:54:00	14:54:00	HND
Operator	Sensor Make / Model / Serial #	Hobbs End	Local End	UTC End	Arriving
Denham	Leica Terrain Mapper - 90513	3196.4	02:47:00	21:47:00	HND

Conditions

Wind Dir (°)	Wind Speed (kts)	Visibility (mi)	Ceiling (ft)	Cloud Cover	Temp. (°C)	Dew Point (°C)	Pressure ("Hg)
170	4	10		Clear	23	4	29.85

Air Speed (kts)	Altitude AGL (ft)	Altitude MSL (ft)	Airfield Elevation (ft)
150		11,000	2,492

Settings

Point Spacing (m)	Point Density (ppsm)	Scan Angle/FOV (°)	Scan Frequency (Hz)	Pulse Rate (kHz)	Laser Power (%)
		40	82	600	29.85

Verify S-Turns Before Mission: Yes

Line #	Direction	Start Time (UTC)	End Time (UTC)	Time On-Line	Satellite	PDOP	Line Notes/Comments
97	S	15:58:00	16:03:00		21	1.4	Alt. 11530 ft Lines 97-94
96	N	16:06:00	16:11:00		21	1.3	
95	S	16:16:00	16:21:00	00:05:00	22	1.1	
94	N	16:25:00	16:28:00	00:03:00	23	1.1	
93	W	16:38:00	16:42:00	00:04:00	23	1.1	Alt. 11160 ft Lines 93-90
92	E	16:46:00	16:50:00	00:04:00	23	1.1	
91	w	16:53:00	16:57:00	00:04:00	25	1.1	
90	E	17:01:00	17:04:00	00:03:00	25	1.1	
89	N	17:13:00	17:16:00	00:03:00	24	1.1	Alt. 10340 ft. Lines 89-88
88	S	17:19:00	17:22:00	00:03:00	24	1.1	
87	N	17:33:00	17:40:00	00:07:00	24	1.1	Alt. 11470 ft. Lines 87-75
86	S	17:44:00	17:50:00	00:06:00	23	1.1	
85	N	17:53:00	17:59:00	00:06:00	21	1.2	
84	S	18:03:00	18:09:00	00:06:00	20	1.2	
83	N	18:30:00	18:18:00	23:48:00	20	1.1	
82	S	18:22:00	18:28:00	00:06:00	19	1.2	
81	N	18:31:00	18:36:00	00:05:00	18	1.2	
80	S	18:40:00	18:45:00	00:05:00	18	1.1	
79	N	18:49:00	18:54:00	00:05:00	17	1.1	
78	S	18:57:00	19:03:00	00:06:00	16	1.2	
77	N	19:06:00	19:11:00	00:05:00	16	1.2	
76	S	19:15:00	19:21:00	00:06:00	16	1.2	
75	N	19:24:00	19:28:00	00:04:00	17	1.1	
74	N	19:35:00	19:39:00	00:04:00	17	1.1	Alt. 10390 ft Lines 74-69
73	S	19:42:00	19:47:00	00:05:00	18	1.1	

Page 1

Verify S-Turns After Mission: Yes

Additional Comments

Continued on next page. Upon Start Up - System Error: Camera NADIR Malfunction.

Mission 1 (20210822) continued

Woolpert Lidar Acquisition Log

Project Info			Date		
Project #	Project Name	Unique ID	Flight Date (UTC)	Day of Year	Flight #
82345	NW AZ Mojave	Day234_90513	08/22/2021	234	

Crew	Equipment	Time			Airports
Pilot	Aircraft Make / Model / Tail #	Hobbs Start	Local Start	UTC Start	Departing
Connolly	Cessna 404 Titan - N7079F	3189.9	07:54:00	14:54:00	HND
Operator	Sensor Make / Model / Serial #	Hobbs End	Local End	UTC End	Arriving
Denham	Leica Terrain Mapper - 90513	3196.4	02:47:00	21:47:00	HND

Conditions							
Wind Dir (°)	Wind Speed (kts)	Visibility (mi)	Ceiling (ft)	Cloud Cover	Temp. (°C)	Dew Point (°C)	Pressure ("Hg)
170	4	0,010		Clear	23	4	29.85
Air Speed (kts)	Altitude AGL (ft)	Altitude MSL (ft)	Airfield Elevation (ft)				
150		11,000	2,492				

Settings					
Point Spacing (m)	Point Density (ppsm)	Scan Angle/FOV (°)	Scan Frequency (Hz)	Pulse Rate (kHz)	Laser Power (%)
		40	82	600	29.85

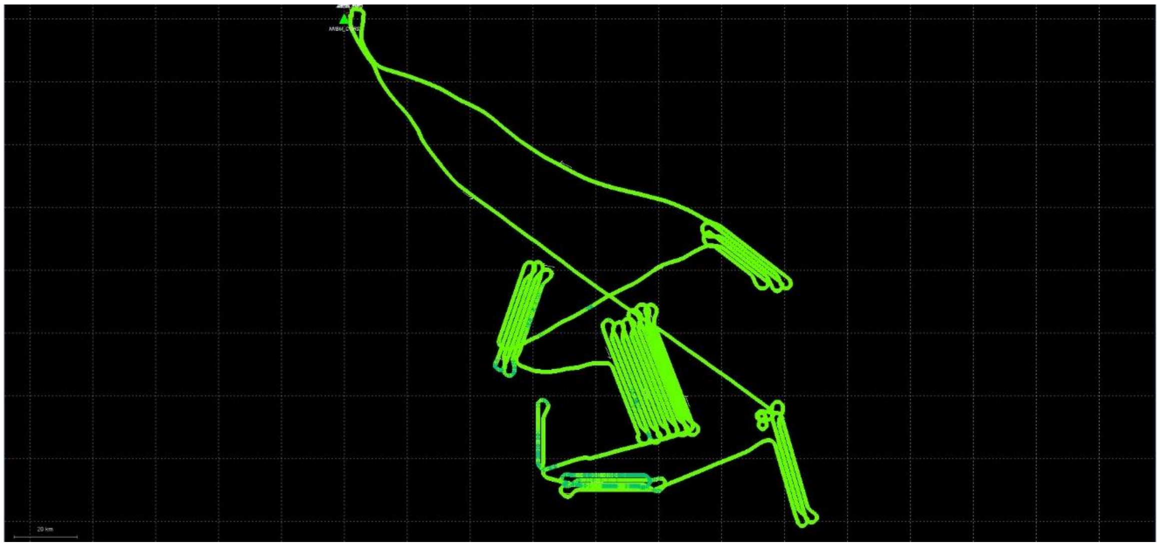
Verify S-Turns Before Mission: Yes

Line #	Direction	Start Time (UTC)	End Time (UTC)	Time On-Line	Satellite	PDOP	Line Notes/Comments
72	N	19:51:00	19:56:00	00:05:00	17	1.1	
71	S	19:59:00	20:04:00	00:05:00	17	1.1	
70	N	20:08:00	20:12:00	00:04:00	17	1.1	
69	S	20:16:00	20:19:00	00:03:00	17	1.1	
68	E	20:36:00	20:38:00	00:02:00	16	1.1	Alt. 13140 ft Lines 68-63
67	W	20:41:00	20:44:00	00:03:00	16	1.1	
66	E	20:48:00	20:51:00	00:03:00	15	1.2	
65	W	20:54:00	20:58:00	00:04:00	15	1.1	
64	E	21:02:00	21:06:00	00:04:00	14	1.5	
63	W	21:09:00	21:13:00	00:04:00	15	1.5	

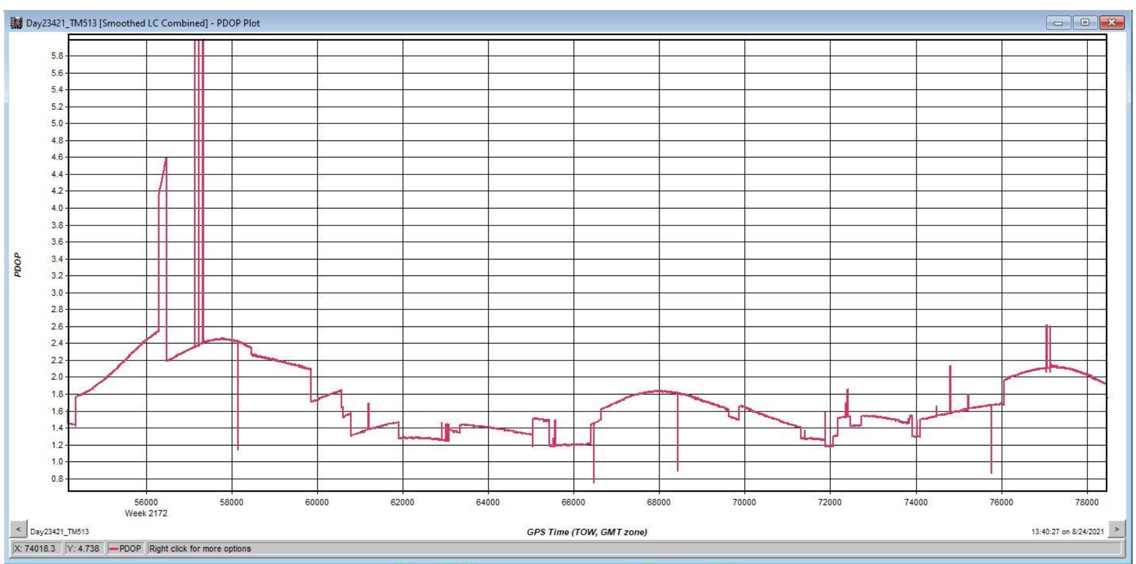
Page 2 | Verify S-Turns After Mission:

Additional Comments

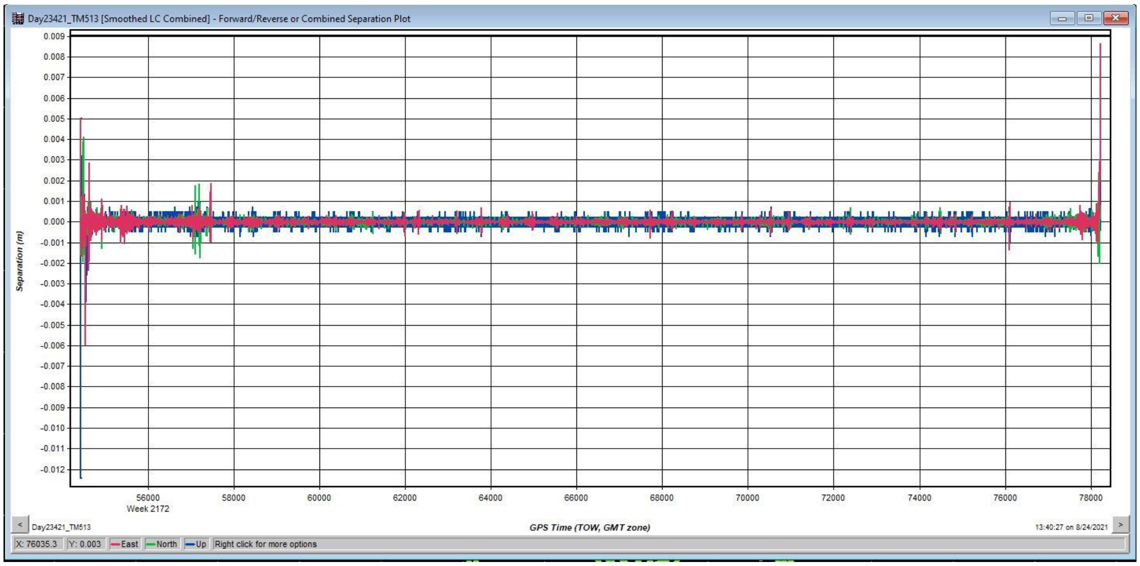
Mission Trajectory



PDOP



Combined Separation



RMS (m)

Mission 2 (20210823)

Flight Log

Woolpert Lidar Acquisition Log

Project Info			Date		
Project #	Project Name	Unique ID	Flight Date (UTC)	Day of Year	Flight #
82345	NW AZ Mojave	Day235_90513	08/23/2021	235	

Crew	Equipment	Time			Airports
Pilot	Aircraft Make / Model / Tail #	Hobbs Start	Local Start	UTC Start	Departing
Connolly	Cessna 404 Titan - N7079F	3169.4	07:53:00	14:53:00	HND
Operator	Sensor Make / Model / Serial #	Hobbs End	Local End	UTC End	Arriving
Denham	Leica Terrain Mapper - 90513	3202.5	02:15:00	21:15:00	HND

Conditions

Wind Dir (°)	Wind Speed (kts)	Visibility (mi)	Ceiling (ft)	Cloud Cover	Temp. (°C)	Dew Point (°C)	Pressure ("Hg)
170	9	10		Clear	21	1	29.87

Air Speed (kts)	Altitude AGL (ft)	Altitude MSL (ft)	Airfield Elevation (ft)
150		11,000	2,492

Settings

Point Spacing (m)	Point Density (ppsm)	Scan Angle/FOV (°)	Scan Frequency (Hz)	Pulse Rate (kHz)	Laser Power (%)
		40	82	600	100

Verify S-Turns Before Mission: Yes

Line #	Direction	Start Time (UTC)	End Time (UTC)	Time On-Line	Satellite	PDOP	Line Notes/Comments
62	E	15:38:00	15:43:00		19	1.2	Alt. 13140 ft Lines 62-55
61	W	15:46:00	15:51:00		19	1.2	
60	E	15:55:00	16:01:00	00:06:00	19	1.3	
59	W	16:04:00	16:10:00	00:06:00	19	1.3	
58	E	16:14:00	16:20:00	00:06:00	21	1.2	
57	W	16:23:00	16:29:00	00:06:00	23	1.1	
56	E	16:32:00	16:38:00	00:06:00	26	1.4	
55	W	16:42:00	16:48:00	00:06:00	27	1.1	
54	N	16:56:00	17:02:00	00:06:00	26	1.2	Alt. 11920 ft Lines 54-41
53	S	17:06:00	17:11:00	00:05:00	26	1.1	
52	N	17:15:00	17:21:00	00:06:00	25	1.1	
51	S	17:24:00	17:30:00	00:06:00	24	1.3	
50	N	17:34:00	17:39:00	00:05:00	24	1.2	
49	S	17:44:00	17:49:00	00:05:00	24	1.2	
48	N	17:53:00	17:59:00	00:06:00	22	1.2	
47	S	18:03:00	18:09:00	00:06:00	22	1.2	
46	N	18:12:00	18:18:00	00:06:00	22	1.2	
45	S	18:22:00	18:28:00	00:06:00	20	1.3	
44	N	18:31:00	18:36:00	00:05:00	19	1.2	
43	S	18:41:00	18:45:00	00:04:00	18	1.4	
42	N	18:49:00	18:53:00	00:04:00	17	1.3	
41	S	18:57:00	19:00:00	00:03:00	17	1.3	
40	S	19:09:00	19:11:00	00:02:00	18	1.2	Alt. 11090 ft Lines 40-30
39	N	19:14:00	19:16:00	00:02:00	18	1.2	
38	S	19:20:00	19:22:00	00:02:00	18	1.2	

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Verify S-Turns After Mission: Yes

Additional Comments

Continued on next page. MR= Mount Roll

Mission 2 (20210823) continued

Woolpert Lidar Acquisition Log

Project Info			Date		
Project #	Project Name	Unique ID	Flight Date (UTC)	Day of Year	Flight #
82345	NW AZ Mojave	Day235_90513	08/23/2021	235	

Crew	Equipment	Time			Airports
Pilot	Aircraft Make / Model / Tail #	Hobbs Start	Local Start	UTC Start	Departing
Connolly	Cessna 404 Titan - N7079F	3169.4	07:53:00	14:53:00	HND
Operator	Sensor Make / Model / Serial #	Hobbs End	Local End	UTC End	Arriving
Denham	Leica Terrain Mapper - 90513	3202.5	02:15:00	21:15:00	HND

Conditions

Wind Dir (°)	Wind Speed (kts)	Visibility (mi)	Ceiling (ft)	Cloud Cover	Temp. (°C)	Dew Point (°C)	Pressure ("Hg)
170	9	0,010		Clear	21	1	29.87

Air Speed (kts)	Altitude AGL (ft)	Altitude MSL (ft)	Airfield Elevation (ft)
150		11,000	2,492

Settings

Point Spacing (m)	Point Density (ppsm)	Scan Angle/FOV (°)	Scan Frequency (Hz)	Pulse Rate (kHz)	Laser Power (%)
		40	82	600	100

Verify S-Turns Before Mission: Yes

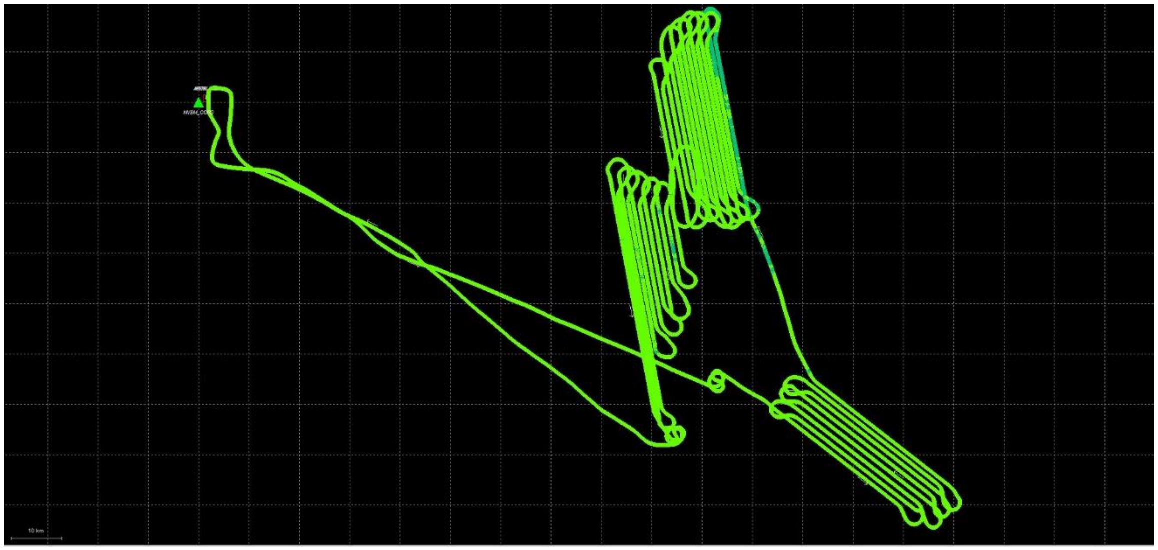
Line #	Direction	Start Time (UTC)	End Time (UTC)	Time On-Line	Satellite	PDOP	Line Notes/Comments
37	N	19:26:00	19:29:00	00:03:00	17	1.5	
36	S	19:33:00	19:36:00	00:03:00	20	1	
35	N	19:40:00	19:44:00	00:04:00	19	1.1	
34	S	19:48:00	19:52:00	00:04:00	19	1.1	MR 19:52
33	N	19:56:00	20:01:00	00:05:00	19	1.1	
32	S	20:05:00	20:13:00	00:08:00	19	1.1	MR 20:08
31	N	20:16:00	20:25:00	00:09:00	17	1.2	Fast 20:22
30	S	20:29:00	20:38:00	00:09:00	17	1.1	

Page 2

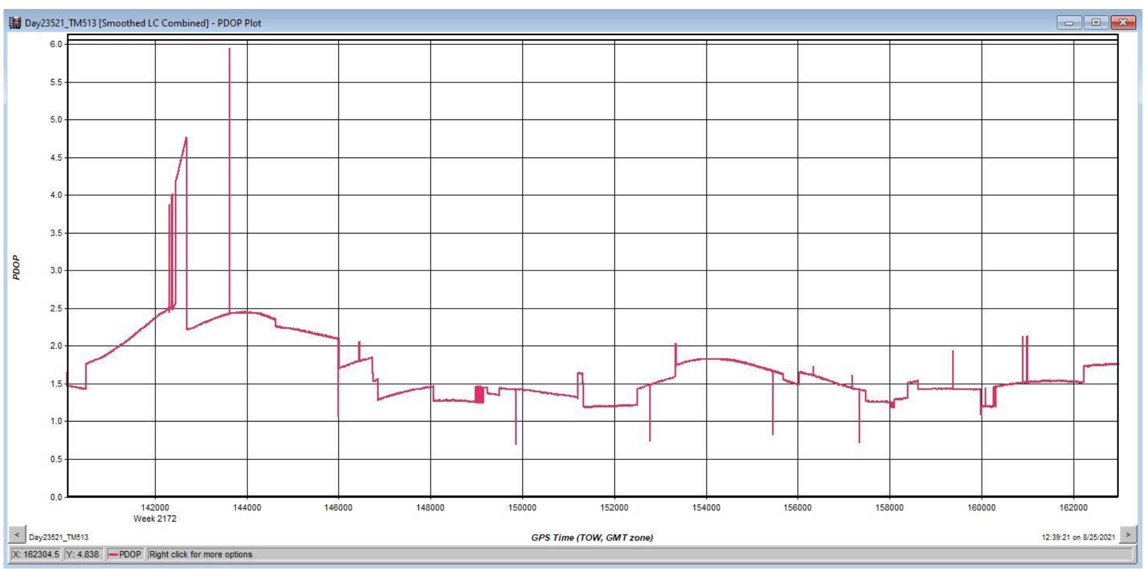
Verify S-Turns After Mission:

Additional Comments

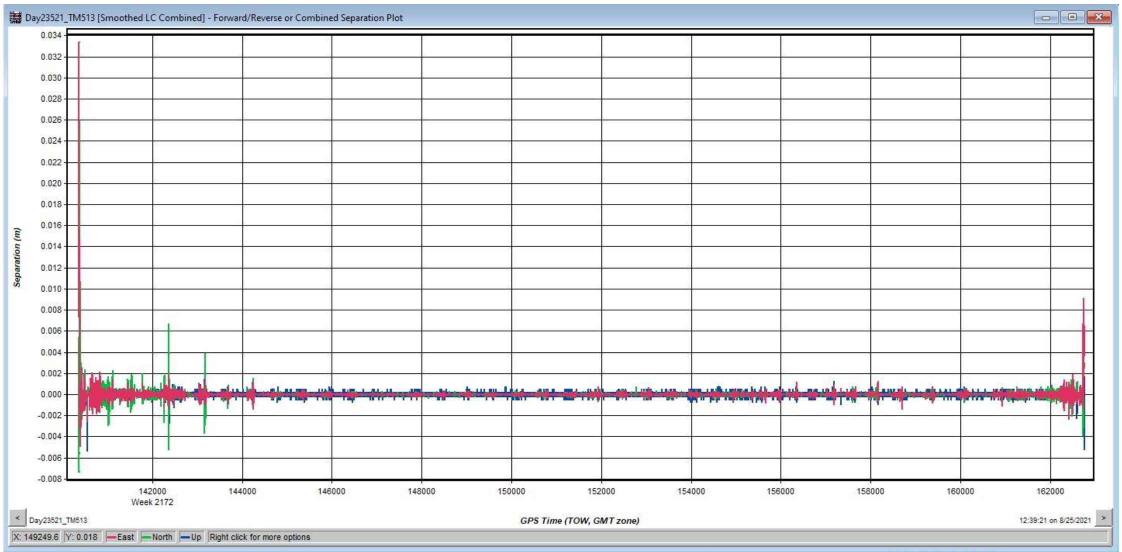
Mission Trajectory



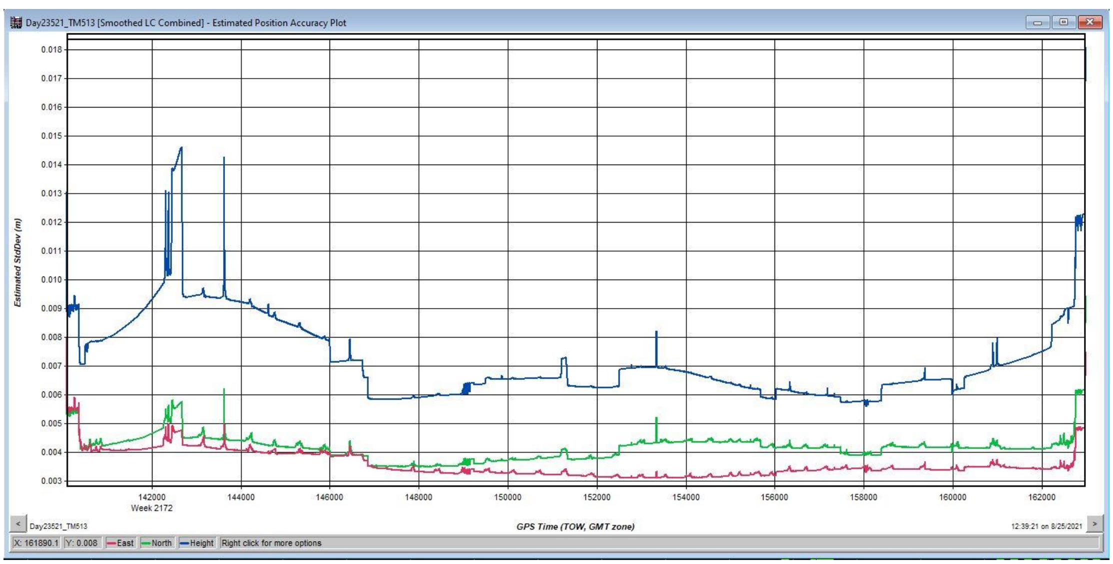
PDOP



Combined Separation



RMS (m)



Mission 3 (20210824)

Flight Log

Woolpert Lidar Acquisition Log

Project Info			Date		
Project #	Project Name	Unique ID	Flight Date (UTC)	Day of Year	Flight #
82345	NW AZ Mojave	Day236_90513	08/24/2021	236	

Crew	Equipment	Time			Airports
Pilot	Aircraft Make / Model / Tail #	Hobbs Start	Local Start	UTC Start	Departing
Connolly	Cessna 404 Titan - N7079F	3202.5	07:55:00	14:55:00	HND
Operator	Sensor Make / Model / Serial #	Hobbs End	Local End	UTC End	Arriving
Denham	Leica Terrain Mapper - 90513	3208.8	02:35:00	21:35:00	HND

Conditions

Wind Dir (°)	Wind Speed (kts)	Visibility (mi)	Ceiling (ft)	Cloud Cover	Temp. (°C)	Dew Point (°C)	Pressure ("Hg)
200	8	10		Clear	24	6	29.94

Air Speed (kts)	Altitude AGL (ft)	Altitude MSL (ft)	Airfield Elevation (ft)
150		11,000	2,492

Settings

Point Spacing (m)	Point Density (ppsm)	Scan Angle/FOV (°)	Scan Frequency (Hz)	Pulse Rate (kHz)	Laser Power (%)
		40	82	600	100

Verify S-Turns Before Mission: Yes

Line #	Direction	Start Time (UTC)	End Time (UTC)	Time On-Line	Satellite	PDOP	Line Notes/Comments
29	N	15:39:00	15:48:00		21	1.2	Alt. 11090 ft
28	S	15:53:00	16:03:00		21	1.3	
27	N	16:07:00	16:17:00	00:10:00	21	1.3	
26	S	16:21:00	16:32:00	00:11:00	24	1.2	
25	N	16:36:00	16:46:00	00:10:00	24	1.1	
24	S	16:50:00	17:02:00	00:12:00	24	1.2	
23	N	17:05:00	17:17:00	00:12:00	23	1.2	
22	S	17:20:00	17:33:00	00:13:00	24	1.2	
21	N	17:36:00	17:53:00	00:17:00	23	1.2	
20	S	17:56:00	18:13:00	00:17:00	21	1.2	
19	N	18:17:00	18:34:00	00:17:00	19	1.3	
18	S	18:38:00	18:56:00	00:18:00	18	1.4	
17	N	18:59:00	19:17:00	00:18:00	20	1.2	
16	S	19:20:00	19:38:00	00:18:00	21	1.3	
15	N	19:41:00	19:59:00	00:18:00	20	1.2	
14	S	20:02:00	20:20:00	00:18:00	19	1.1	
13	N	20:23:00	20:41:00	00:18:00	18	1.2	
12	S	20:44:00	21:02:00	00:18:00	17	1.2	

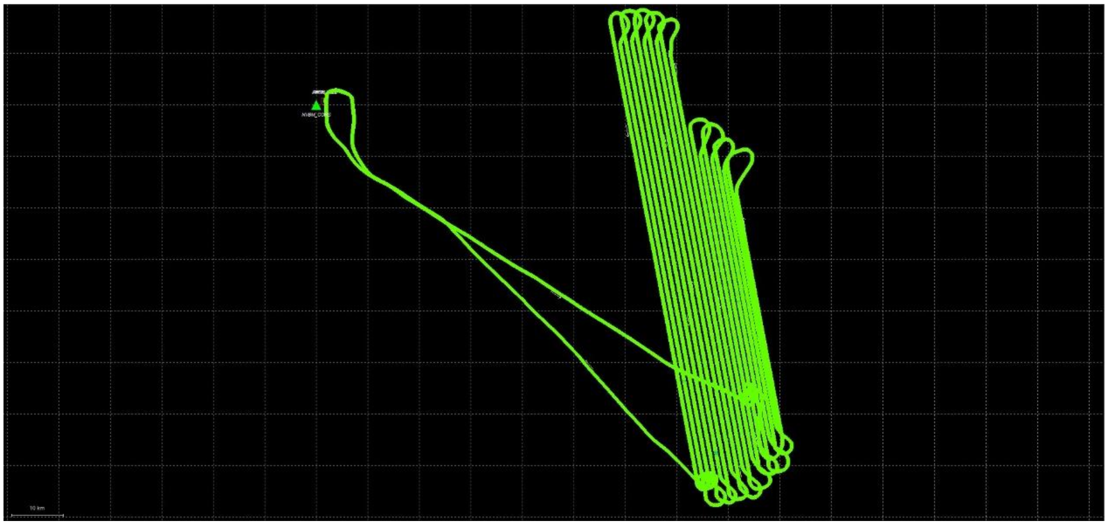
Page 1

Verify S-Turns After Mission: Yes

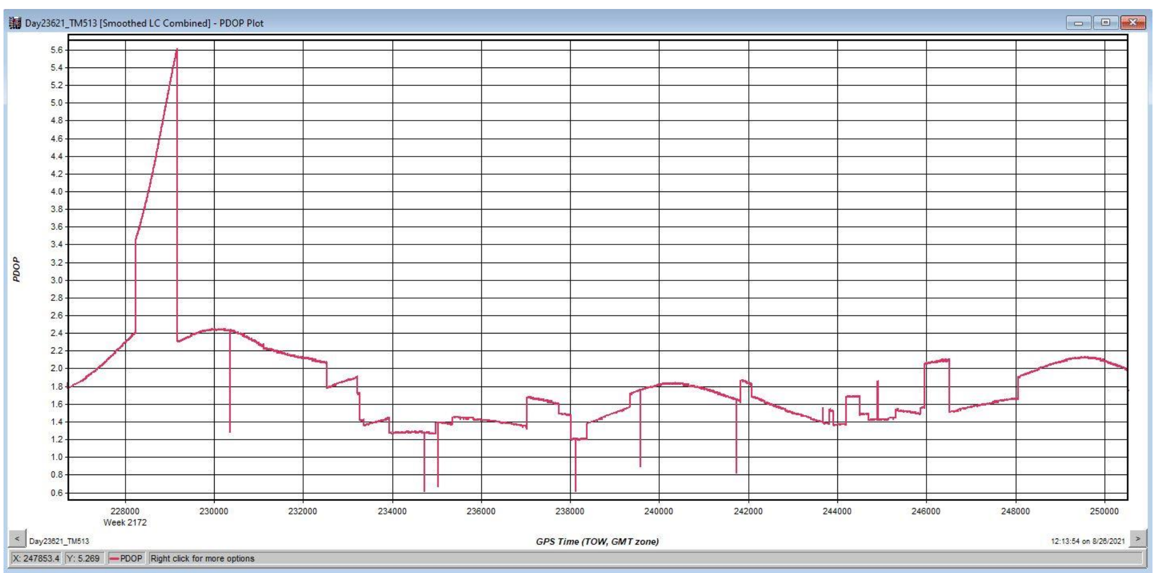
Additional Comments

Updrafts late in Mission Today.

Mission Trajectory



PDOP



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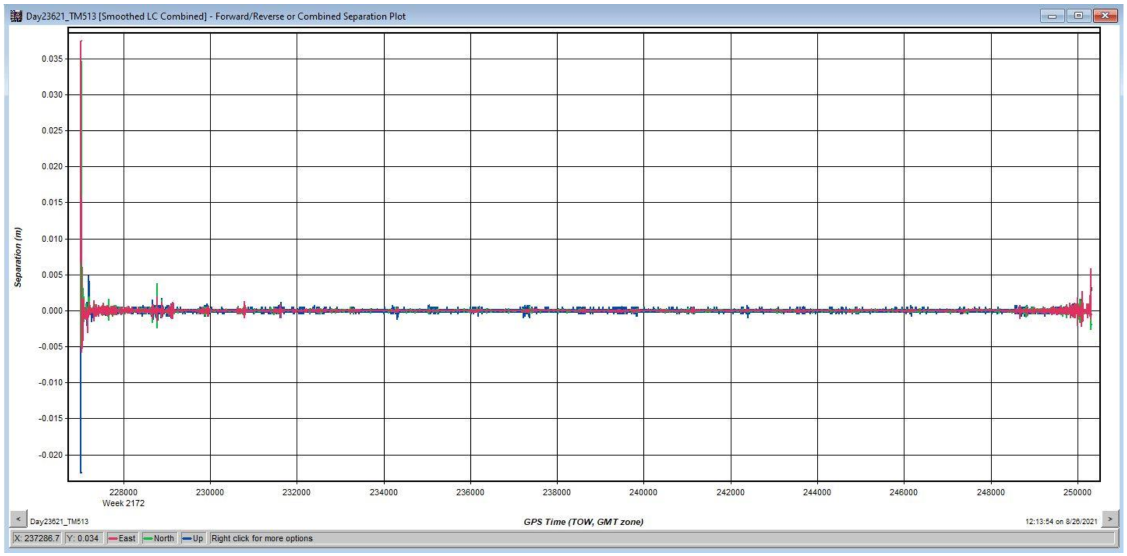
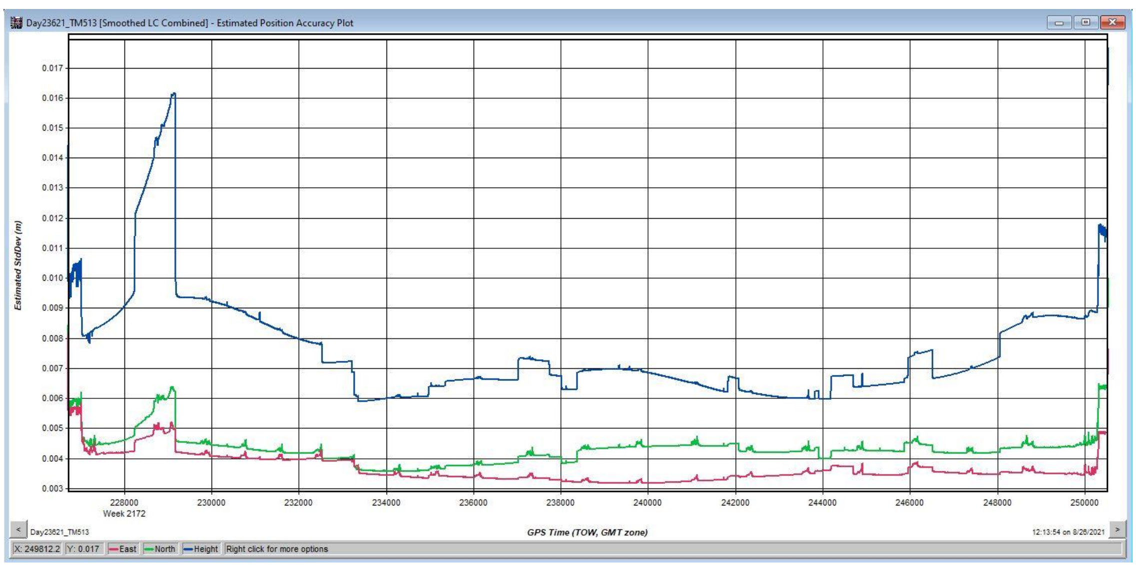


RMS (m)



Mission 4 (20210825)

Flight Log

Woolpert Lidar Acquisition Log

Project Info			Date		
Project #	Project Name	Unique ID	Flight Date (UTC)	Day of Year	Flight #
82345	NW AZ Mojave	Day237_90513	08/25/2021	237	

Crew	Equipment	Time			Airports
Pilot	Aircraft Make / Model / Tail #	Hobbs Start	Local Start	UTC Start	Departing
Connolly	Cessna 404 Titan - N7079F	3208.8	07:55:00	14:55:00	HND
Operator	Sensor Make / Model / Serial #	Hobbs End	Local End	UTC End	Arriving
Denham	Leica Terrain Mapper - 90513	3213.5	12:57:00	19:57:00	HND

Conditions

Wind Dir (°)	Wind Speed (kts)	Visibility (mi)	Ceiling (ft)	Cloud Cover	Temp. (°C)	Dew Point (°C)	Pressure ("Hg)
190	12	10		Clear	27	-1	29.98

Air Speed (kts)	Altitude AGL (ft)	Altitude MSL (ft)	Airfield Elevation (ft)
150		11,000	2,492

Settings

Point Spacing (m)	Point Density (ppsm)	Scan Angle/FOV (°)	Scan Frequency (Hz)	Pulse Rate (kHz)	Laser Power (%)
		40	82	600	100

Verify S-Turns Before Mission: Yes

Line #	Direction	Start Time (UTC)	End Time (UTC)	Time On-Line	Satellite	PDOP	Line Notes/Comments
11	N	15:39:00	15:57:00		19	1.4	Alt. 11090 ft
10	S	16:00:00	16:19:00		20	1.4	
9	N	16:23:00	16:42:00	00:19:00	21	1.2	
8	S	16:46:00	17:06:00	00:20:00	21	1.2	
7	N	17:09:00	17:28:00	00:19:00	21	1.4	
6	S	17:32:00	17:52:00	00:20:00	22	1.2	
5	N	17:55:00	18:15:00	00:20:00	20	1.2	
4	S	18:18:00	18:37:00	00:19:00	18	1.2	
3	N	18:42:00	18:57:00	00:15:00	18	1.2	
2	S	19:00:00	19:15:00	00:15:00	17	1.2	
1	N	19:18:00	19:31:00	00:13:00	16	1.3	

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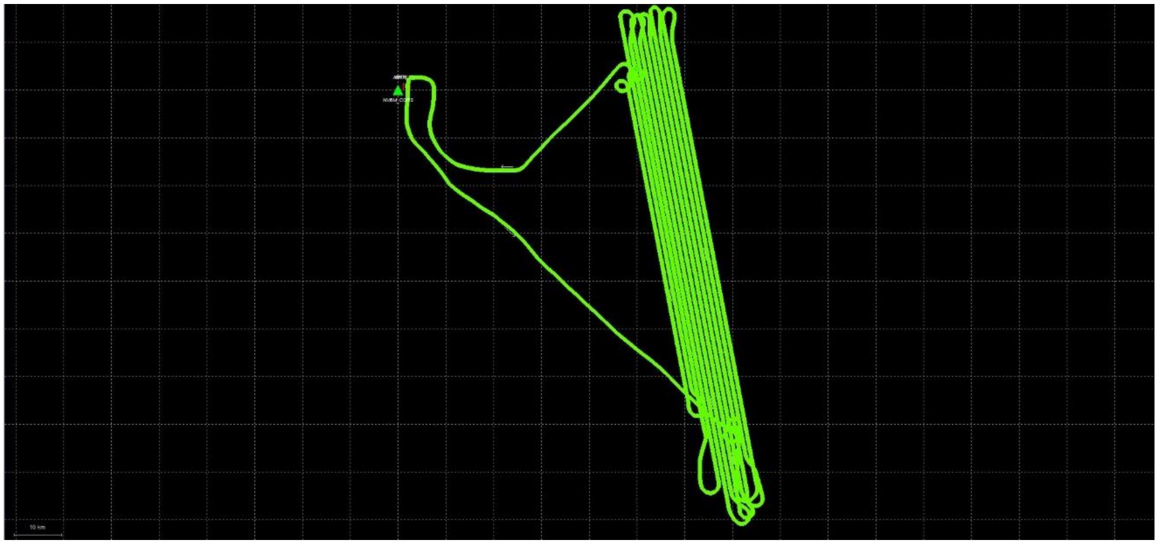
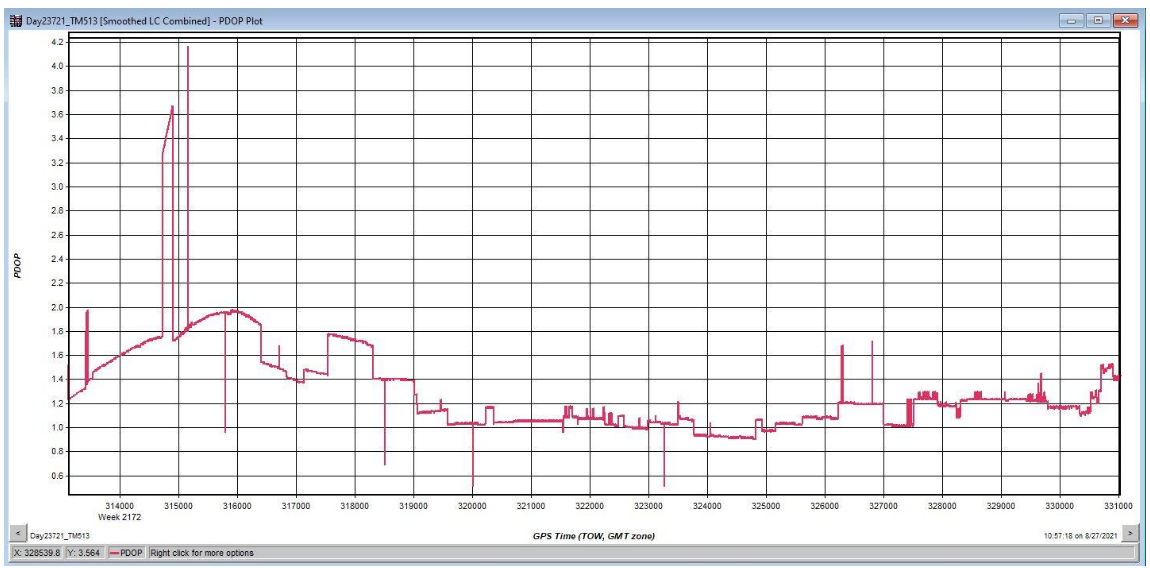
Verify S-Turns After Mission: Yes

Additional Comments

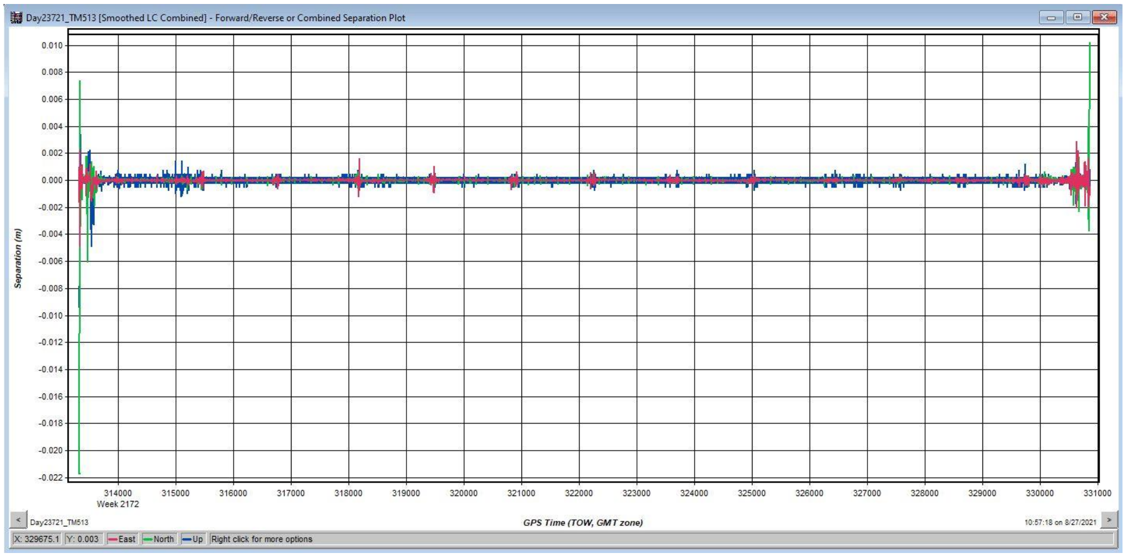
Mission Trajectory



PDOP



Combined Separation



RMS (m)