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Florida Keys 3DEP Lidar

Technical Data Report

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Cover Photo: An image taken by one of NV5 Geospatial's flight operators showing a view out the airplane window over the Florida Keys 3DEP Lidar project area.

PROJECT SUMMARY

This photo taken by NV5 Geospatial acquisition staff shows a scenic view of the Florida Keys 3DEP Lidar site in Florida.

Introduction

In January of 2020, NV5 Geospatial was contracted by the United States Geological Survey (USGS) to bring the 2018/2019 National Oceanic and Atmospheric Administration (NOAA) Florida Keys Light Detection and Ranging (lidar) dataset into USGS 3D Elevation Program (3DEP) compliance. The Florida Keys 3DEP Lidar site covers approximately 1.36 million acres in the state of Florida, along the Gulf Coast of the United States. The area of interest stretched from Miami, Florida in the north to the Key West Islands in the south. NV5 Geospatial conducted all lidar acquisition of the project area between November 20th, 2018 and March 23rd, 2019. Although the data collection for NOAA was originally for topobathymetric and shoreline mapping purposes, NV5 Geospatial treated this delivery as though it were topographic in nature to ensure it met USGS 3DEP specifications.

This report accompanies the delivered lidar data, and documents contract specifications, data acquisition procedures, processing methods, and analysis of the final dataset including lidar accuracy and density. Acquisition dates and acreage are shown in Table 1, a complete list of contracted deliverables provided to USGS is shown in Table 2, and the project extent is shown in Figure 1.

Table 1: Acquisition dates, acreage, and data types collected for the Florida Keys 3DEP Lidar project

Project Site	Project Acres	Acquisition Dates	Data Type
Florida Keys 3DEP Lidar	1,366,060	11/20/2018 - 03/23/2019	Lidar

Deliverable Products

Table 2: Products delivered to USGS for the Florida Keys 3DEP Lidar site

<table>
<tr><th colspan="2">Florida Keys 3DEP Lidar Products
Projection: UTM Zone 17 North
Horizontal Datum: NAD83 (2011)
Vertical Datum: NAVD88 (GEOID 12B)
Units: Meters</th></tr>
<tr><td>Points</td><td>LAS v 1.4
• All Classified Returns</td></tr>
<tr><td>Rasters</td><td>1.0 Meter Cloud Optimized GeoTiffs (*.tif)
• Hydroflattened Bare Earth Digital Elevation Model (DEM)
• Intensity Images
• DZ Orthos</td></tr>
<tr><td>Vectors</td><td>Shapefiles (*.shp)
• Area of Interest
• Tile Index (1,000 x 1,000 meters)
• Ground Survey Shapes
ESRI File Geodatabase (*.gdb)
• Flightline Index
• Flightline Swath Coverage Extents
• Water’s Edge Breaklines
• Bridge Breaklines
• Ground Survey Shapes</td></tr>
</table>

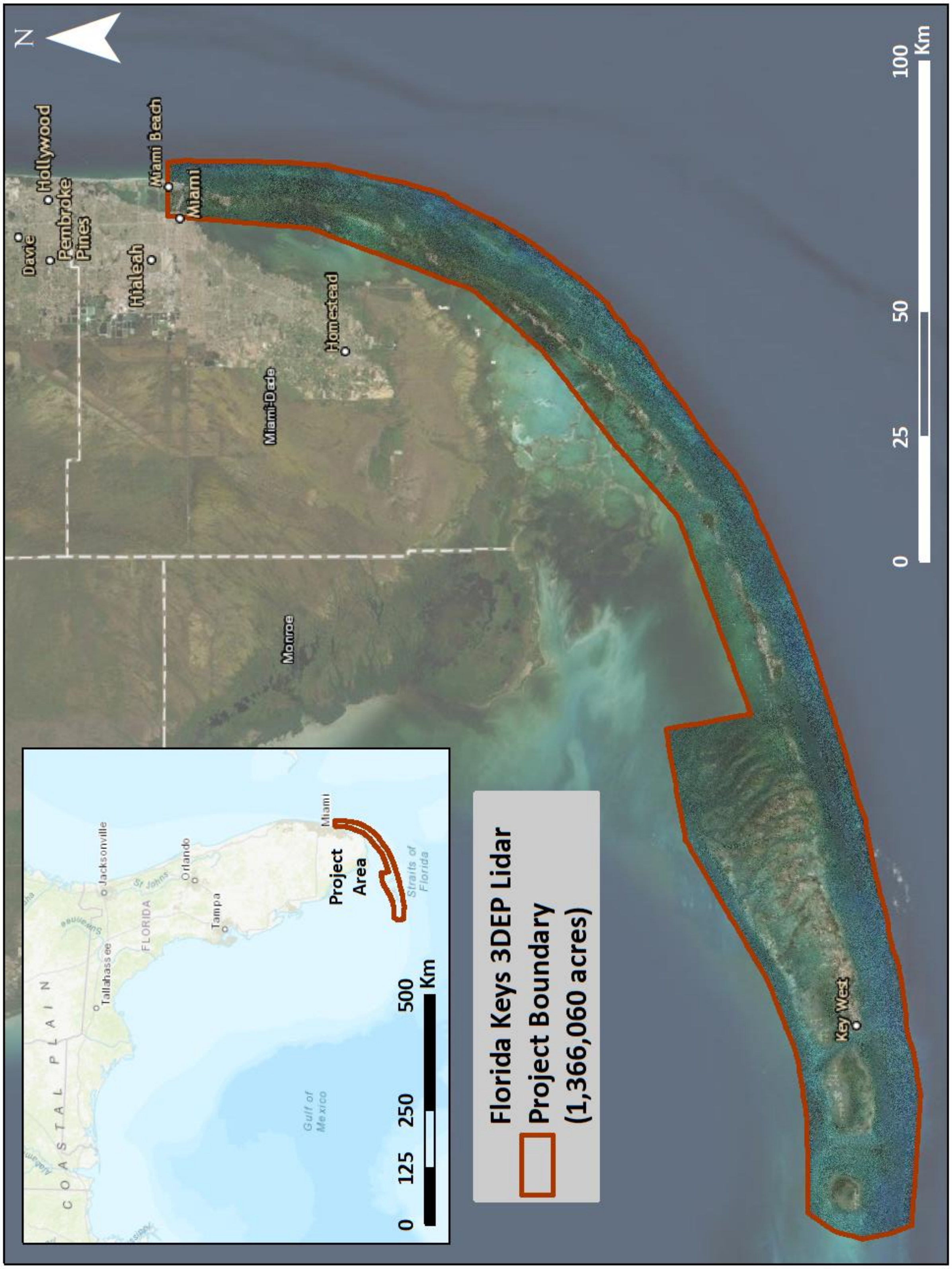

Figure 1: Location map of the Florida Keys 3DEP Lidar site in Florida

This photo shows a view of the Florida Keys project area taken from NV5 Geospatial's Cessna Caravan.

Planning

In preparation for data collection, NV5 Geospatial reviewed the project area and developed a specialized flight plan to ensure complete coverage of the Florida Keys 3DEP Lidar study area at the target point density of ≥2.0 points/m^2. Acquisition parameters including orientation relative to terrain, flight altitude, pulse rate, scan angle, and ground speed were adapted to optimize flight paths and flight times while meeting all contract specifications.

Flights over shoreline areas were planned during optimal conditions with low wind and wave conditions whenever possible, and within 20% of the Mean Range of tide around Mean Lower Low Water (MLLW). NV5 Geospatial acquisition managers oversaw all logistical considerations including private property access and coordination of NOTAMs prior to flights.

Airborne Lidar Survey

The lidar survey was accomplished using a Riegl VQ-880-G green laser system (or equivalent) mounted in a Cessna Caravan. The Riegl VQ-880-G uses a green wavelength (ʎ=532 nm) laser that is capable of collecting high resolution vegetation and topography data, as well as penetrating the water surface with minimal spectral absorption by water. The Riegl VQ-880-G also contains an integrated NIR laser (ʎ=1064 nm) that was used for water surface modeling and refraction purposes only. The recorded waveform enables range measurements for all discernible targets for a given pulse. It is not uncommon for some types of surfaces (e.g., dense vegetation or water) to return fewer pulses to the lidar sensor than the laser originally emitted. The discrepancy between first return and overall delivered density will vary depending on terrain, land cover, and the prevalence of water bodies. All discernible laser returns were processed for the output dataset. Table 3 summarizes the settings used to yield an average first return pulse density of ≥ 2 pulses/m^2 over the Florida Keys 3DEP Lidar project area.

Table 3: lidar specifications and survey settings

lidar Survey Settings & Specifications	
Acquisition Dates	11/20/2018 - 03/23/2019
Aircraft Used	Cessna Caravan
Sensor	Riegl
Laser	VQ-880-G, GII, or GH
Maximum Returns	15
Resolution/Density	≥2 pulses/m^2
Nominal Pulse Spacing	0.71 m
Survey Altitude (AGL)	400 m
Survey speed	140 knots
Field of View	40^o
Mirror Scan Rate	80 revolutions per second
Target Pulse Rate	245 kHz
Pulse Length	1.5 ns
Laser Pulse Footprint Diameter	28 cm
Central Wavelength	532 nm
Pulse Mode	MTA (multiple times around)
Beam Divergence	0.7 mrad
Swath Width	291 m
Swath Overlap	30%
Intensity	16-bit
Accuracy	RMSEZ ≤ 10 cm NVA ≤ 19.6 cm VVA ≤ 29.4 cm

All areas were surveyed with an opposing flight line side-lap of ≥30% (≥60% overlap) in order to reduce laser shadowing and increase surface laser painting. To accurately solve for laser point position (geographic coordinates x, y and z), the positional coordinates of the airborne sensor and the attitude of the aircraft were recorded continuously throughout the lidar data collection mission. Position of the aircraft was measured twice per second (2 Hz) by an onboard differential GPS unit, and aircraft attitude was measured 200 times per second (200 Hz) as pitch, roll and yaw (heading) from an onboard inertial measurement unit (IMU). To allow for post-processing correction and calibration, aircraft and sensor position and attitude data are indexed by GPS time.

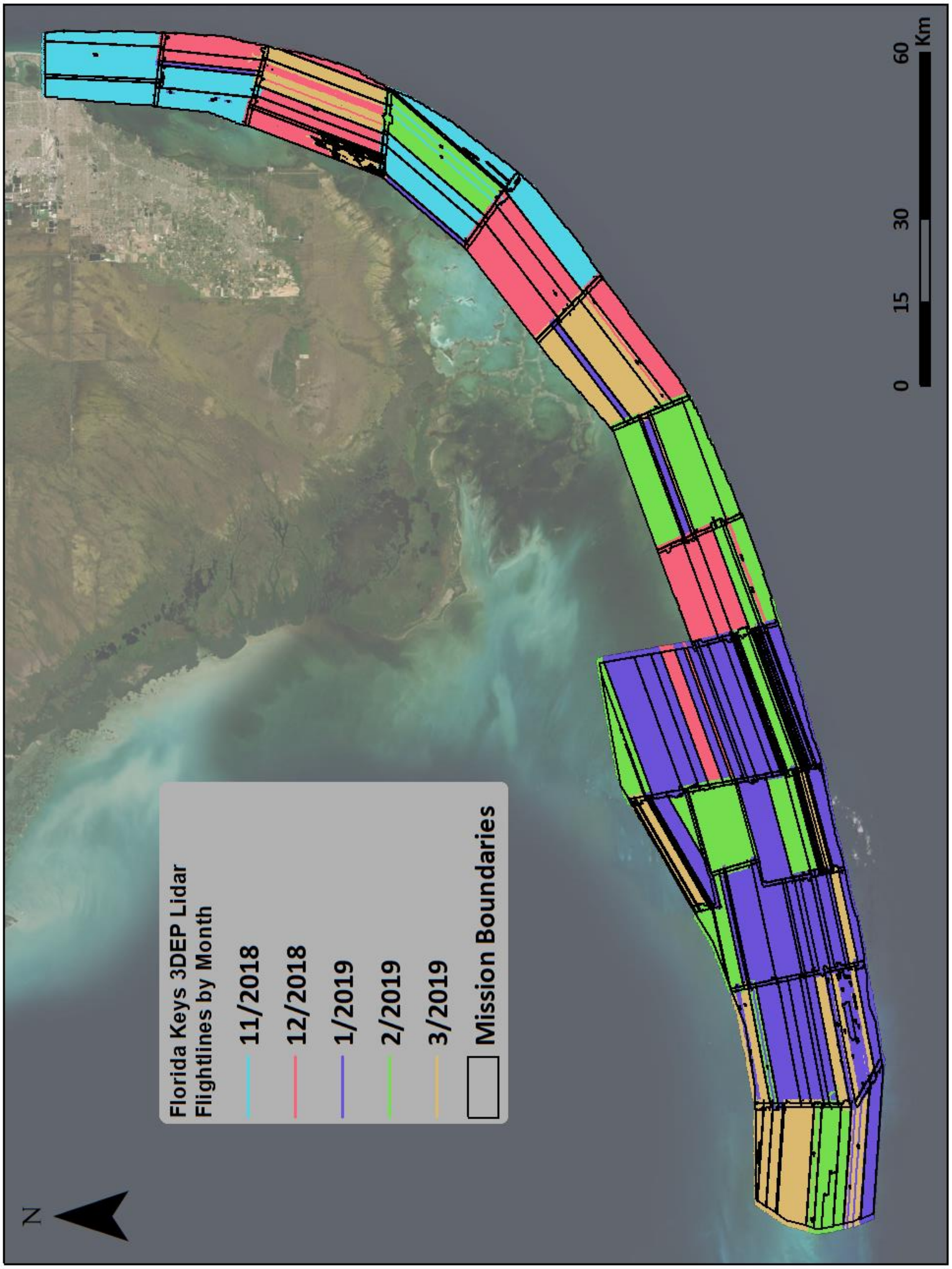

Figure 2: Florida Keys 3DEP Lidar Flightline Map

Table 4: Flight Missions by Date

Date	Flight #	Start Time (Adjusted GPS)	End Time (Adjusted GPS)
11/20/2018	1	226774272	226783963
11/21/2018	1	226859787	226867454
11/25/2018	1	227201884	227220219
11/26/2018	1	227289070	227302720
11/29/2018	1	227528964	227551651
11/30/2018	1	227622023	227641468
12/1/2018	1	227711519	227719235
12/2/2018	1	227798929	227800305
12/4/2018	1	227977240	227985560
12/5/2018	1	228064980	228074265
12/6/2018	1	228164747	228165698
12/7/2018	1	228236501	228249862
12/16/2018	1	229008357	229023208
12/17/2018	1	229093062	229106901
12/18/2018	1	229187003	229192923
12/19/2018	1	229264836	229281331
12/29/2018	1	230132623	230133983
12/30/2018	1	230216406	230223054
1/1/2019	1	230391684	230404524
1/2/2019	1	230477823	230485073
1/3/2019	1	230563600	230579919
1/4/2019	1	230647900	230662221
1/5/2019	1	230750279	230754185
1/7/2019	1	230919798	230919835
1/8/2019	1	230993293	231003296
1/9/2019	1	231072833	231087465
1/10/2019	1	231180708	231193855
1/11/2019	1	231254160	231269546
1/12/2019	1	231340386	231360433
1/13/2019	1	231421812	231441766
1/15/2019	1	231598618	231610905
1/16/2019	1	231681558	231698905

1/17/2019	1	231690191	231780280
1/18/2019	1	231856814	231871480
1/19/2019	1	231941801	231958772
1/30/2019	1	232899560	232900067
1/31/2019	1	232983289	232998014
2/1/2019	1	233069501	233083251
2/2/2019	1	233156826	233182497
2/3/2019	1	233243188	233262580
2/6/2019	1	233508494	233526186
2/7/2019	1	233594620	233608129
2/15/2019	1	234275903	234290467
2/15/2019	2	234294456	234300780
2/16/2019	1	234361091	234378248
2/17/2019	1	234446736	234447930
2/26/2019	1	235246526	235256977
2/27/2019	1	235313373	235330869
2/28/2019	1	235399506	235414854
3/1/2019	1	235480405	235493776
3/1/2019	2	235500022	235505270
3/2/2019	1	235568783	235585276
3/3/2019	1	235658975	235675809
3/4/2019	1	235738793	235741436
3/4/2019	2	235755214	235761519
3/5/2019	1	235829300	235844021
3/7/2019	1	236008185	236029059
3/8/2019	1	236089470	236104354
3/9/2019	1	236174921	236187094
3/10/2019	1	236260926	236264196
3/11/2019	1	236346823	236349499
3/12/2019	1	236435431	236436365
3/13/2019	1	236522547	236525074
3/16/2019	1	236788916	236798788
3/20/2019	1	237145172	237158581
3/21/2019	1	237220426	237225060
3/23/2019	1	237382185	237388116

Ground Control

Ground control surveys were conducted to support the airborne acquisition. Ground control data were used to geospatially correct the aircraft positional coordinate data and to perform quality assurance checks on final lidar data.

Base Stations

Base stations were utilized for collection of ground survey points using real time kinematic (RTK), post processed kinematic (PPK), and fast static (FS) survey techniques.

Base station locations were selected with consideration for optimal location for GSP coverage. NV5 Geospatial utilized nine permanent RTN stations for the Florida Keys 3DEP Lidar project. Three base stations were from the VRS-Now network and six were from the Florida Permanent Reference Network (FPRN). The position, precision, and network of each base station have been provided in Table 5. Record positions were held for all base stations. NV5 Geospatial's professional land surveyor, Steven J. Hyde (PSM#6436) oversaw the use of all base stations and certified the ground survey work.

Table 5: Permanent Real-Time Network (RTN) stations utilized for the Florida Keys 3DEP Lidar acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00. Units are in meters.

Station ID	Latitude	Longitude	Ellipsoid (meters)	Network	Held?
FLKW	24° 33' 13.26664"	-81° 45' 15.39914"	-10.257	FPRN	YES
FLKW*	24° 39' 33.67173"	-81° 31' 20.54518"	-11.211	VRSNOW	YES
FLMA	24° 43' 06.59490"	-81° 04' 06.74239"	-11.711	FPRN	YES
FLMB	25° 46' 57.83786"	-80° 08' 14.16764"	-15.518	FPRN	YES
FLMK	24° 43' 33.36203"	-81° 02' 56.70329"	-13.903	FPRN	YES
FLPK	24° 57' 47.22531"	-80° 34' 05.39838"	-13.201	FPRN	YES
FLUM	25° 43' 54.86870"	-80° 09' 48.52710"	-5.285	VRSNOW	YES
HMST	25° 28' 13.58298"	-80° 29' 19.63111"	-16.134	VRSNOW	YES
HOME	25° 30' 03.79565"	-80° 33' 00.43217"	-19.134	FPRN	YES

* Trimble VRS-Now and FPRN independently include a station named FLKW. It is not a duplicate.

NV5 Geospatial triangulated static Global Navigation Satellite System (GNSS) data (1 Hz recording frequency) from each base station with nearby Continuously Operating Reference Stations (CORS) using the Online Positioning User Service (OPUS[1]) to ensure alignment with the National Spatial Reference System (NSRS), updating record positions as necessary. Multiple independent sessions over the same base station were processed to confirm antenna height measurements and to refine position accuracy. The five NGS CORS utilized during OPUS Project processing are listed in Table 6.

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[1] OPUS is a free service provided by the National Geodetic Survey to process corrected monument positions. http://www.ngs.noaa.gov/OPUS.

Table 6: NGS CORS utilized with OPUS Project. Published NAD83(2011) coordinates were held and can be retrieved from http://www.ngs.noaa.gov/CORS/.

CORS used in OPUS Project		
FLBN	FLF1	GACR
GNVL	ZMA1	

Ground Survey Points (GSPs)

Ground survey points were collected using real time kinematic (RTK), post-processed kinematic (PPK), and fast-static (FS) survey techniques. For RTK surveys, a roving receiver receives corrections from a nearby base station or Real-Time Network (RTN) via radio or cellular network, enabling rapid collection of points with relative errors less than 1.5 cm horizontal and 2.0 cm vertical. PPK and FS surveys compute these corrections during post-processing to achieve comparable accuracy. RTK and PPK surveys record data while stationary for at least five seconds, calculating the position using at least three one-second epochs. FS surveys record observations for up to fifteen minutes on each GSP in order to support longer baselines. All GSP measurements were made during periods with a Position Dilution of Precision (PDOP) of ≤ 3.0 with at least six satellites in view of the stationary and roving receivers. See Table 7 for NV5 Geospatial ground survey equipment information.

GSPs were collected in areas where good satellite visibility was achieved on paved roads and other hard surfaces such as gravel or packed dirt roads. GSP measurements were not taken on highly reflective surfaces such as center line stripes or lane markings on roads due to the increased noise seen in the laser returns over these surfaces. GSPs were collected within as many flightlines as possible; however, the distribution of GSPs depended on ground access constraints and monument locations and may not be equitably distributed throughout the study area (Figure 6).

Table 7: Trimble equipment identification

Receiver Model	Antenna	OPUS Antenna ID	Serial Numbers	Use
Trimble R8 Model 2	Integrated Antenna	TRMR8_GNSS	0649, 8595	Rover, Static
Trimble R8 Model 3	Integrated Antenna	TRMR8_GNSS3	9860	Rover

Land Cover Class

In addition to ground survey points, land cover class check points were collected throughout the study area to evaluate vertical accuracy. Vertical accuracy statistics were calculated for all land cover types to assess confidence in the lidar derived ground models across land cover classes (Table 8).

Table 8: Land Cover Types and Descriptions

Land cover type	Land cover code	Example	Description	Accuracy Type
Shrub Land	SHRUB, SH		Maintained or low growth herbaceous shrub lands	VVA
Tall Grass	TALL_GRASS, TG		Herbaceous grasslands in advanced stages of growth	VVA
Forest	FOREST, FR, FO		Forested areas	VVA

Land cover type	Land cover code	Example	Description	Accuracy Type
Bare Earth	BARE, BE		Areas of bare earth surface	NVA
Urban	URBAN, UA		Areas dominated by urban development, including parks	NVA

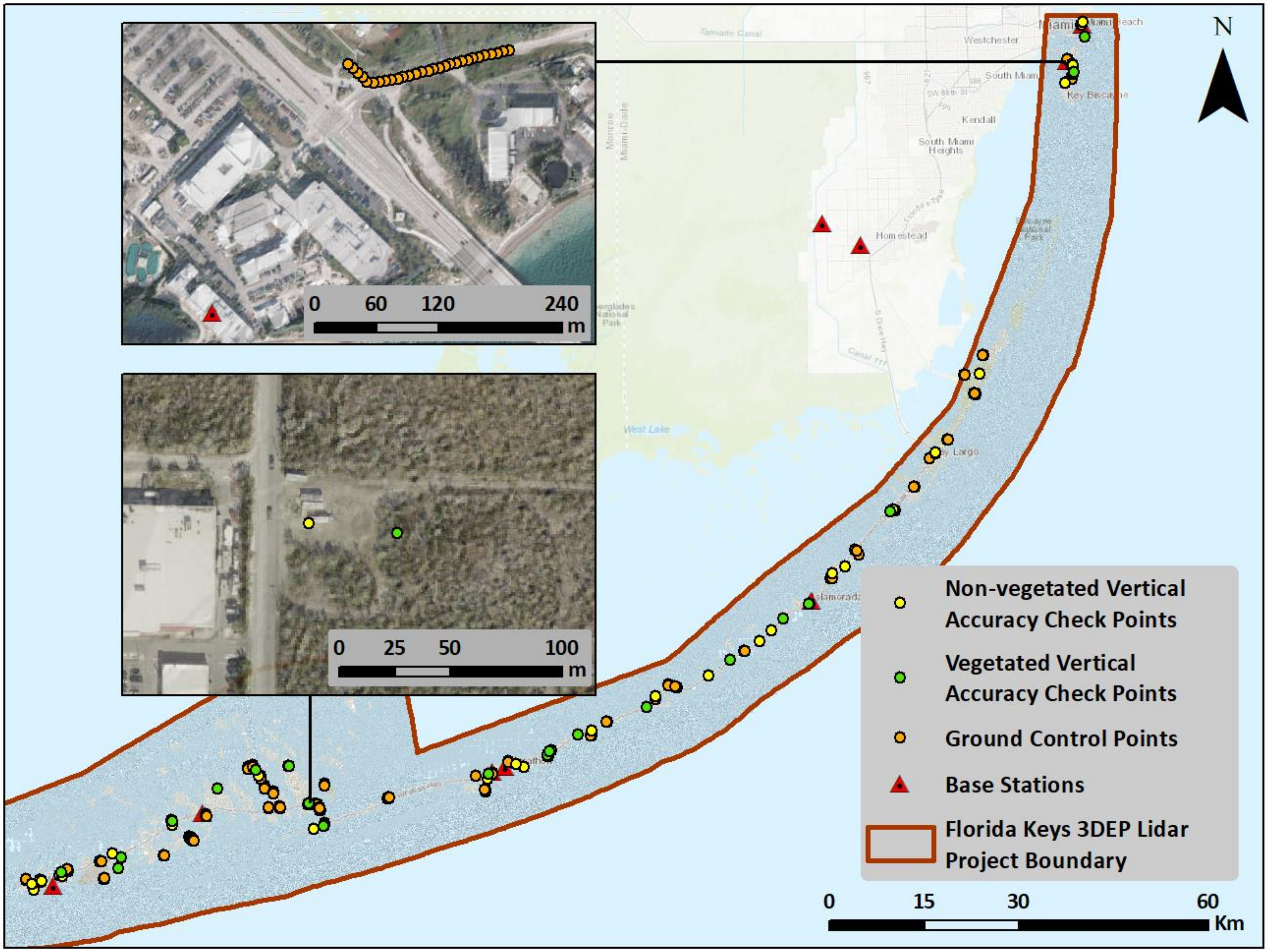


Figure 3: Ground survey location map

This image shows a 3-meter cross section of palm trees in the Florida Keys 3DEP project area, colored by classification.

Lidar Data Calibration

Upon completion of data acquisition, NV5 Geospatial processing staff initiated a suite of automated and manual techniques to process the data into a geo-referenced point cloud ready for refraction processing and classification routines. Solutions for Smoothed Best Estimates of Trajectory (SBET) were processed using Applanix POSPac 8.3 SP3 using their Trimble® CenterPoint™ Post-Processed Real-Time Extended (PP-RTX) solution. This process utilizes the GPS and IMU data recorded onboard the aircraft, real-time data from Trimble's global reference station infrastructure, and advanced positioning and compression algorithms to calculate a highly accurate SBET for each mission.

Laser return point position computations were completed in Riegl's SDCImport and RiWorld software using the SBET and raw range information. After extracting the laser swaths, swath-to-swath geometric corrections were found using least square fit regression of matching tie plane objects in RiProcess. Individual lifts were adjusted to match vertical ground control points where available, and then integrated with corresponding overlapping lifts. Any remaining swath-swath discrepancies were further resolved using Terrasolid's TerraMatch application.

Bathymetric Refraction

The water surface models used for refraction were generated using elevation information from the point cloud. Where possible, points from the NIR channel were preferred due to the clean characteristics of water surface returns from that wavelength. However, because the NIR and green channels are not spatially and temporally coincident in the VQ-880-G system, where substantial wave action was present the green channels were used instead. Advanced classification routines were employed to ensure above-surface spray and below-surface backscatter points were not included in the model. Points were automatically classified, passed through filters appropriate to surface characteristics, and then manually edited to obtain the most accurate representation of the water surface. Models were created for each flight line to accommodate water level changes due to tide or other temporal factors.

The refraction correction was applied to submerged points using NV5 Geospatial's proprietary software Las Monkey. Points were flagged to refract based on their position relative to the triangulated irregular network model representing the water surface. Using the information from the trajectory and water surface model, each point was spatially corrected for refraction through the water column based on the angle of incidence of the laser to the model.

The resulting point cloud was classified into its final scheme using both manual and automated techniques (Table 9). To bring the dataset into USGS 3DEP compliance, the point classification of the original NOAA data was updated. Changes that were made to point classification can be seen in Table 10.

Table 9: ASPRS LAS classification standards applied to the Florida Keys 3DEP Lidar dataset

Classification Number	Classification Name	Classification Description
1	Default/Unclassified	Laser returns that are not included in the ground class, composed of vegetation and anthropogenic features
1-O	Adjacent Lift Unclassified	Adjacent lift Unclassified associated with areas of overlap bathy bottom where temporal bathymetric differences are present
1-W	Edge Clip/Overlap	Laser returns at the outer edges of flightlines that are geometrically unreliable
2	Ground	Laser returns that are determined to be ground using automated and manual cleaning algorithms
2-O	Adjacent Lift Ground	Adjacent lift Ground associated with areas of overlap bathy bottom where temporal bathymetric differences are present
7-W	Noise	Laser returns that are often associated with artificial points below the ground surface
9	Water Surface	Laser returns that are determined to be water using automated and manual cleaning algorithms
9-O	Adjacent Lift Water Surface	Adjacent lift Water Surface associated with areas of overlap bathy bottom where temporal bathymetric differences are present
17	Bridge	Bridge decks
18-W	High Noise	Laser returns that are often associated with birds or scattering from reflective surfaces
20	Ignored Ground	Ground points proximate to water’s edge breaklines; ignored for correct model creation
40	Bathymetric Bottom	Bathymetric point (e.g., seafloor or riverbed; also known as submerged topography)
40-O	Overlap Bathymetric Bottom	Denotes bathymetric bottom temporal changes from varying lifts, not utilized in the bathymetric point class
43	Submerged Feature	Submerged object, not otherwise specified (e.g., wreck, rock, submerged piling)
45	Water Column	Refracted returns not determined to be water surface or bathymetric bottom
45-O	Adjacent Lift Water Column	Adjacent lift Water Column associated with areas of overlap bathy bottom where temporal bathymetric differences are present

Table 10: USGS/NOAA Point Classification Crosswalk

USGS Task Order Classes		NOAA Task Order Classes		Crosswalk Notes
Geometrically Unreliable Points	1-Witheld	1-Overlap	Edge Clip	NOAA classing adapted to latest USGS specification, referencing the witheld/ overlap email distributed 7/21/20
Unclassified	1	1	Unclassified	
Ground	2	2	Ground	
Low Noise	7-Witheld	7	Noise	
Water Surface	9	41	Water Surface	
Bridge Decks	17	N/A	-	Added classifcation for 3DEP Compliance
High Noise	18-Witheld	N/A	-	
Ignored Ground	20	N/A	-	
Snow	21	N/A	-	Classification not used
Temporal Exclusion	22	N/A	-	
Bathymetric Bottom	40	40	Bathymetric Bottom	
Submerged Feature	43	43	Submerged Feature	
-	N/A	42	Derived Water Surface	Classifcation not used in NOAA deliveries; will not be delivered to USGS
-	N/A	44	S-57 Object	
Water Column	45	45	Water Column	
Overlap Bathymetric Bottom	40 - Overlap	46	Overlap Bathymetric Bottom	NOAA classing adapted to latest USGS specification, referencing the witheld/ overlap email distributed 7/21/20
Adjacent Lift Unclassified	1 - Overlap	71	Adjacent Lift Unclassified	
Adjacent Lift Ground	2 - Overlap	72	Adjacent Lift Ground	
Adjacent Lift Water Surface	9 - Overlap	81	Adjacent Lift Water Surface	
Adjacent Lift Water Column	45 - Overlap	85	Adjacent Lift Water Column	
-	N/A	139	Withheld Tail Clip	Classifcation not used in NOAA deliveries, will not be delivered to USGS

Table 11: Lidar processing workflow

Lidar Processing Step	Software Used
GNSS/IMU processing to create smoothed best estimate of trajectory using PP-RTX technology.	Applanix POSPac v.8.3 Service Pack 3
Extract raw laser data and calculate laser point positions. Calculation combines raw ranging information, processed SBET, automated determination of MTA (Multiple-Time-Around) zone, and coordinate system information to extract and georeference each laser return.	Riegl SDCImport v.2.3 Riegl RiWorld v.5.1
Sensor boresight. Per-lift geometric adjustments based on least-squares adjustment of feature matched tie planes.	Riegl RiProcess v.1.8
Apply refraction correction and depth bias correction to subsurface returns.	LAS Monkey v.2.6.2 (NV5 Proprietary)
Import raw laser points into manageable blocks to perform manual relative accuracy calibration and filter erroneous points. Classify ground points for individual flight lines.	TerraScan v.19
Using ground classified points per flight line, perform automated line-to-line calibrations for system attitude parameters (pitch, roll, and heading). Match data to vertical control points. Assess relative accuracies between overlapping lifts and relative within each lift and swath.	TerraMatch v.19 Las Product Creator v.3.4 (NV5 Proprietary)
Classify resulting data to ground and other client designated ASPRS classifications (Table 9). Assess statistical absolute accuracy via direct comparisons of ground classified points to ground control survey data.	TerraScan v.19 TerraModeler v.19 Las Monkey v.2.6.2 (NV5 Proprietary)
Generate hydroflattened bare earth models as triangulated surfaces. Export all surface models as Cloud Optimized GeoTIFFs (*.tif) format at a 1-meter pixel resolution.	LAS Product Creator 3.4 (NV5 Proprietary)
Export intensity images as Cloud Optimized GeoTIFFs at a 1-meter pixel resolution.	LAS Product Creator 3.4 (NV5 Proprietary)

Hydroflattening and Water's Edge Breaklines

Coastal waters and lakes within the project area that met the USGS hydroflattening specification of 2 acres or greater were classified and hydroflattened to a consistent water level. There were no rivers within the defined project area. The hydroflattening process eliminates artifacts in the digital terrain model caused by both increased variability in ranges and dropouts in laser returns due to the low reflectivity of water.

Due to the variability in ocean water levels throughout project acquisition and the mapping of bathymetry rather than only terrestrial terrain, a non-standard approach to hydro flattening coastal waters was discussed with USGS and applied here. The approach first incorporated the official NOAA shoreline shape to maintain as much agreement as possible between national datasets. The resolution of this shoreline, however, was not entirely sufficient to meet USGS requirements so some additional adjustments were applied. An initial watermask was generated from the NOAA shoreline corresponding to a -0.5m elevation. This application was particularly useful in areas of developed shoreline composed primarily of docks and canals. The initial watermask was then iteratively grown into adjacent areas where the terrain elevation was below -0.5m. This was necessary to prevent small sinks adjacent to the ocean and increase the resolution and accuracy of the final shoreline. The final watermask used for hydroflattening the ocean represents a -0.5m elevation contour. Along with coastal waters, lakes were flattened by assigning a consistent elevation for an entire polygon.

Elevations for lakes were then obtained from the filtered lidar returns and merged with the shoreline watermask to create the final breaklines. As with the coastal waters, lakes were assigned a consistent elevation for an entire polygon. Water boundary breaklines were then incorporated into the hydroflattened DEM by enforcing triangle edges (adjacent to the breakline) to the elevation values of the breakline. This implementation corrected interpolation along the hard edge. Water surfaces were obtained from a TIN of the 3-D water edge breaklines resulting in the final hydroflattened model (Figure 4).

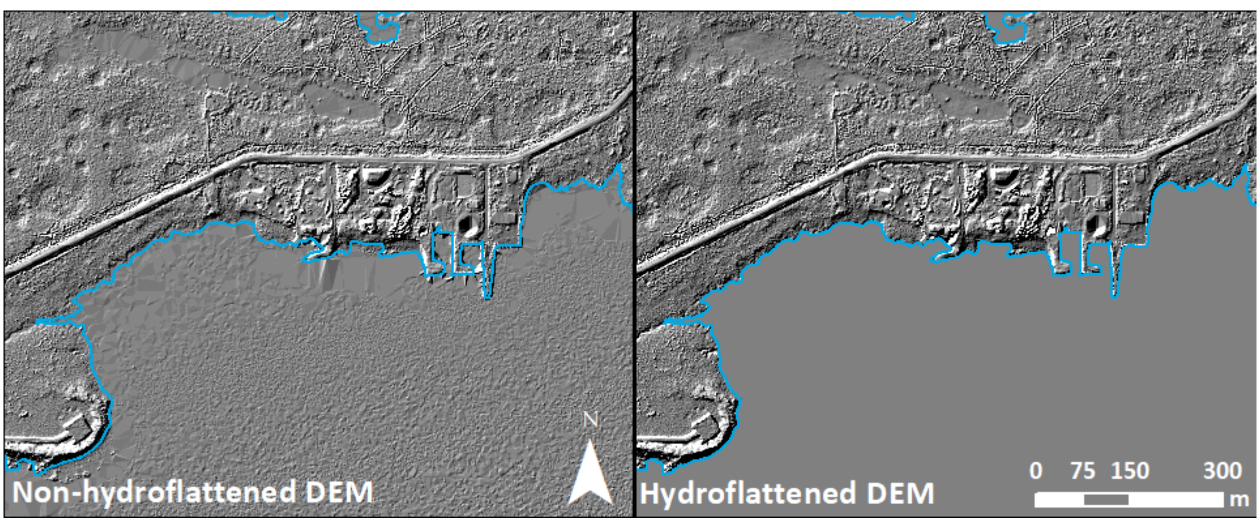
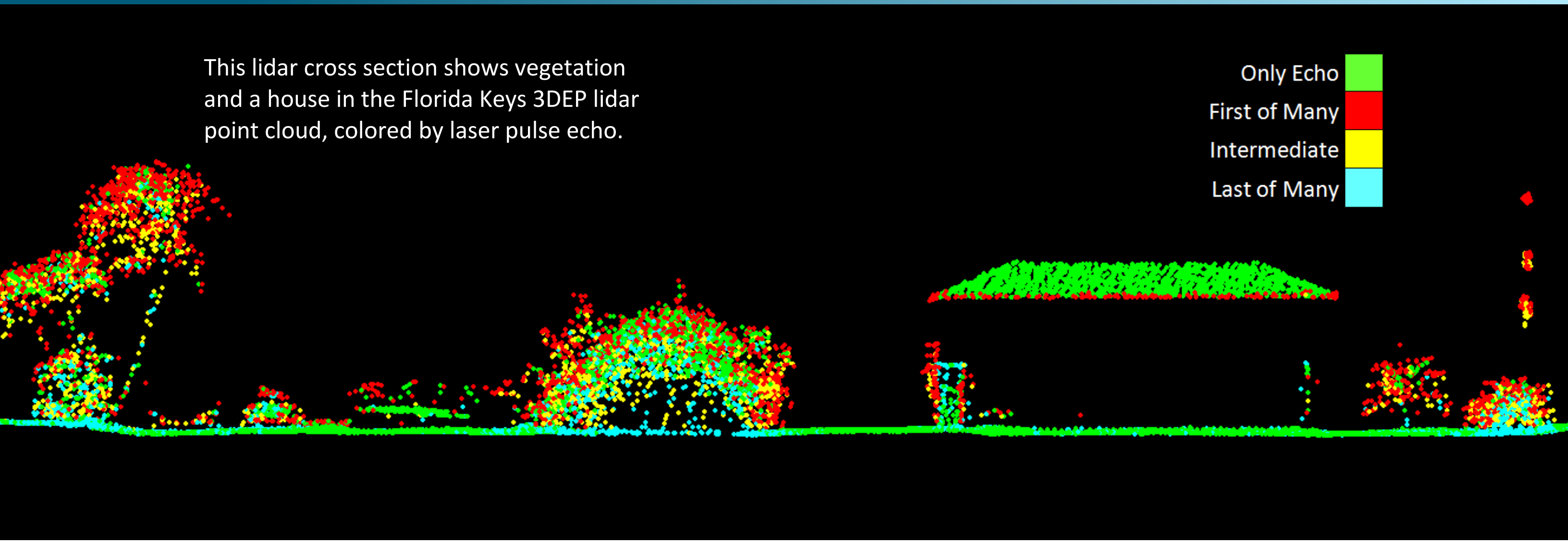


Figure 4: Example of hydroflattening in the Florida Keys 3DEP Lidar dataset



Lidar Density

The acquisition parameters were designed to acquire an average first-return density of 2 points/m^2. First return density describes the density of pulses emitted from the laser that return at least one echo to the system. Multiple returns from a single pulse were not considered in first return density analysis. Some types of surfaces (e.g., breaks in terrain, water and steep slopes) may have returned fewer pulses than originally emitted by the laser. First returns typically reflect off the highest feature on the landscape within the footprint of the pulse. In forested or urban areas the highest feature could be a tree, building or power line, while in areas of unobstructed ground, the first return will be the only echo and represents the bare earth surface.

The density of ground-classified lidar returns was also analyzed for this project. Terrain character, land cover, and ground surface reflectivity all influenced the density of ground surface returns. In vegetated areas, fewer pulses may penetrate the canopy, resulting in lower ground density.

The average first-return density of lidar data for the Florida Keys 3DEP Lidar project was 11.44 points/m^2 while the average ground classified density was 5.46 points/m^2 (Table 12). The statistical and spatial distributions of first return densities and classified ground return densities per 100 m x 100 m cell are portrayed in Figure 5 through Figure 6.

Table 12: Average lidar point densities

Classification	Point Density
First-Return	11.44 points/m^2
Ground Classified	5.46 points/m^2

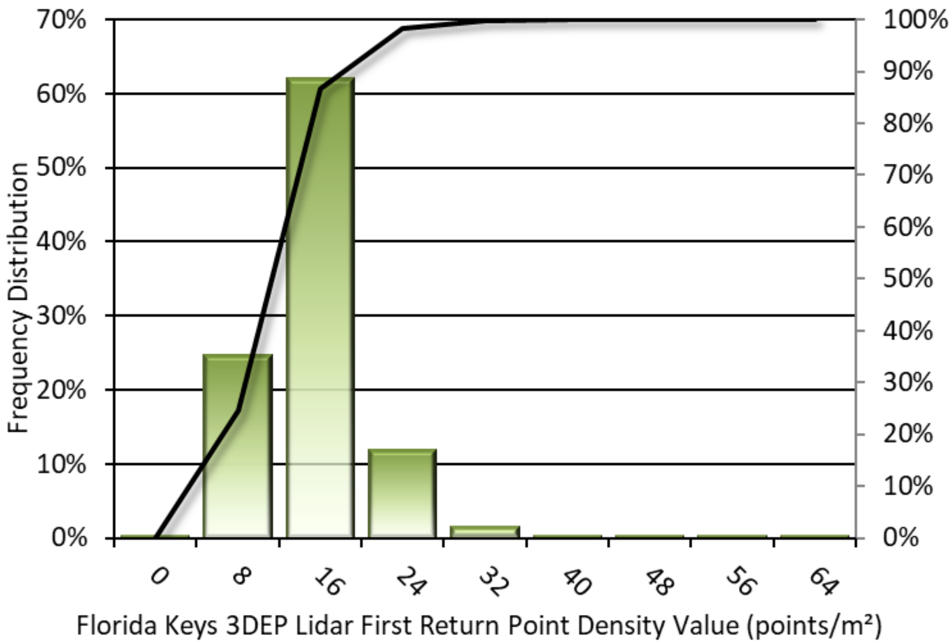


Figure 5: Frequency distribution of first return point density values per 100 x 100 m cell

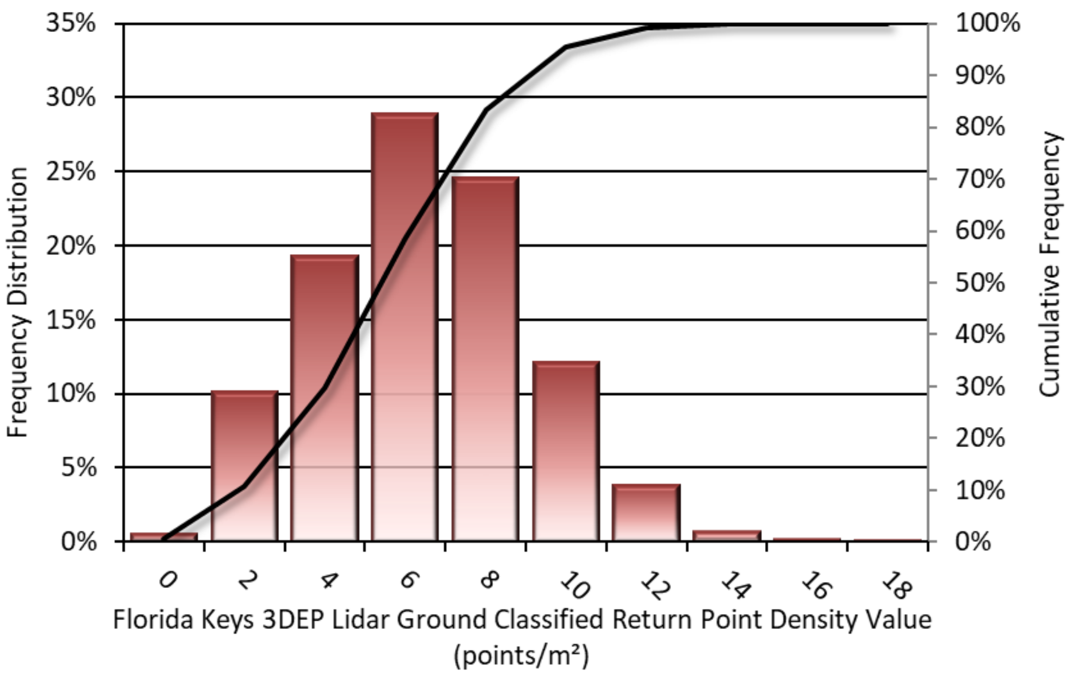


Figure 6: Frequency distribution of ground-classified return point density values per 100 x 100 m cell

Lidar Accuracy Assessments

The accuracy of the lidar data collection can be described in terms of absolute accuracy (the consistency of the data with external data sources) and relative accuracy (the consistency of the dataset with itself). See Appendix A for further information on sources of error and operational measures used to improve relative accuracy.

Lidar Non-Vegetated Vertical Accuracy

Absolute accuracy was assessed using Non-vegetated Vertical Accuracy (NVA) reporting designed to meet guidelines presented in the FGDC National Standard for Spatial Data Accuracy[2]. NVA compares known ground check point data that were withheld from the calibration and post-processing of the lidar point cloud to the triangulated surface generated by the unclassified lidar point cloud as well as the derived gridded bare earth DEM. NVA compares known ground quality assurance point data collected on open, bare earth surfaces with level slope (<20°) to the triangulated surface generated by the lidar points. NVA is a measure of the accuracy of lidar point data in open areas where the lidar system has a high probability of measuring the ground surface and is evaluated at the 95% confidence interval (1.96 * RMSE), as shown in Table 13.

The mean and standard deviation (sigma σ) of divergence of the ground surface model from ground check point coordinates are also considered during accuracy assessment. These statistics assume the error for x, y and z is normally distributed, and therefore the skew and kurtosis of distributions are also considered when evaluating error statistics. For the Florida Keys 3DEP Lidar survey, 36 ground check points were withheld from the calibration and post-processing of the lidar point cloud, with resulting non-vegetated vertical accuracy of 0.077 meters as compared to the classified LAS, and 0.078 meters as compared to the bare earth DEM, with 95% confidence.

NV5 Geospatial also assessed absolute accuracy using 2,088 ground control points. Although these points were used in the calibration and post-processing of the lidar point cloud, they still provide a good indication of the overall accuracy of the lidar dataset, and therefore have been provided in Table 13 and Figure 9.

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[2] Federal Geographic Data Committee, ASPRS POSITIONAL ACCURACY STANDARDS FOR DIGITAL GEOSPATIAL DATA EDITION 1, Version 1.0, NOVEMBER 2014. http://www.asprs.org/PAD-Division/ASPRS-POSITIONAL-ACCURACY-STANDARDS-FOR-DIGITAL-GEOSPATIAL-DATA.html.

Table 13: Absolute accuracy (NVA) results

Non-Vegetated Vertical Accuracy			
	NVA - Ground Check Points (LAS)	NVA - Ground Check Points (DEM)	Ground Control Points
Sample	36 points	36 points	2,088 points
95% Confidence (1.96*RMSE)	0.077 m	0.078 m	0.055 m
Average	0.003 m	0.006 m	0.004 m
Median	0.006 m	0.006 m	0.006 m
RMSE	0.039 m	0.040 m	0.028 m
Standard Deviation (1σ)	0.040 m	0.040 m	0.027 m

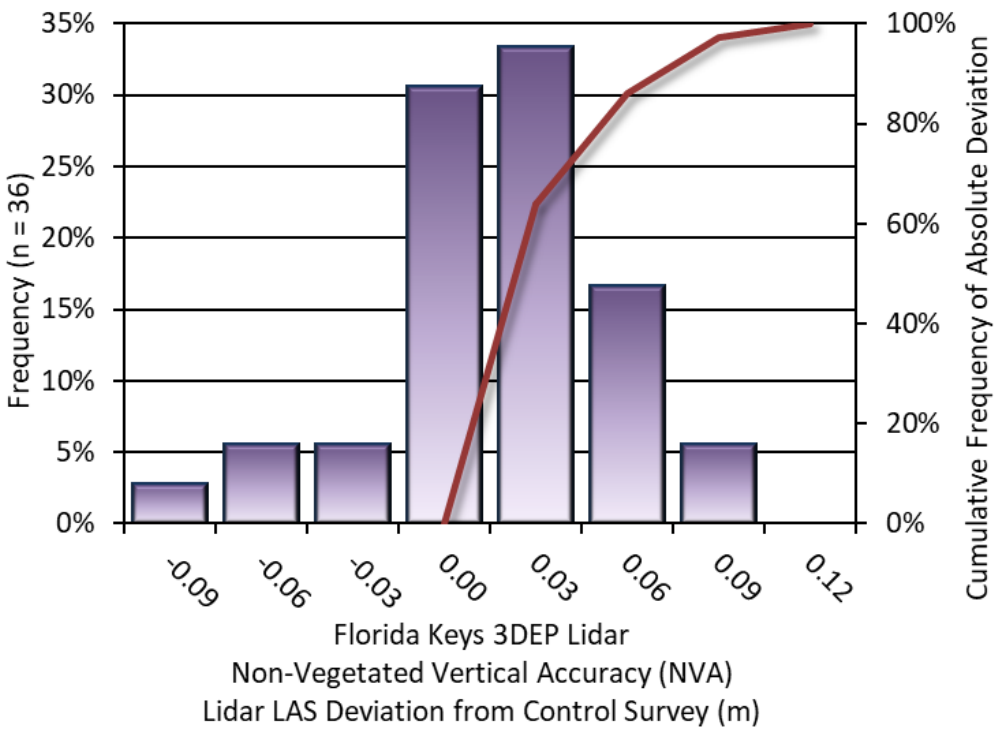

Figure 7: Frequency histogram for lidar las deviation from ground check point values

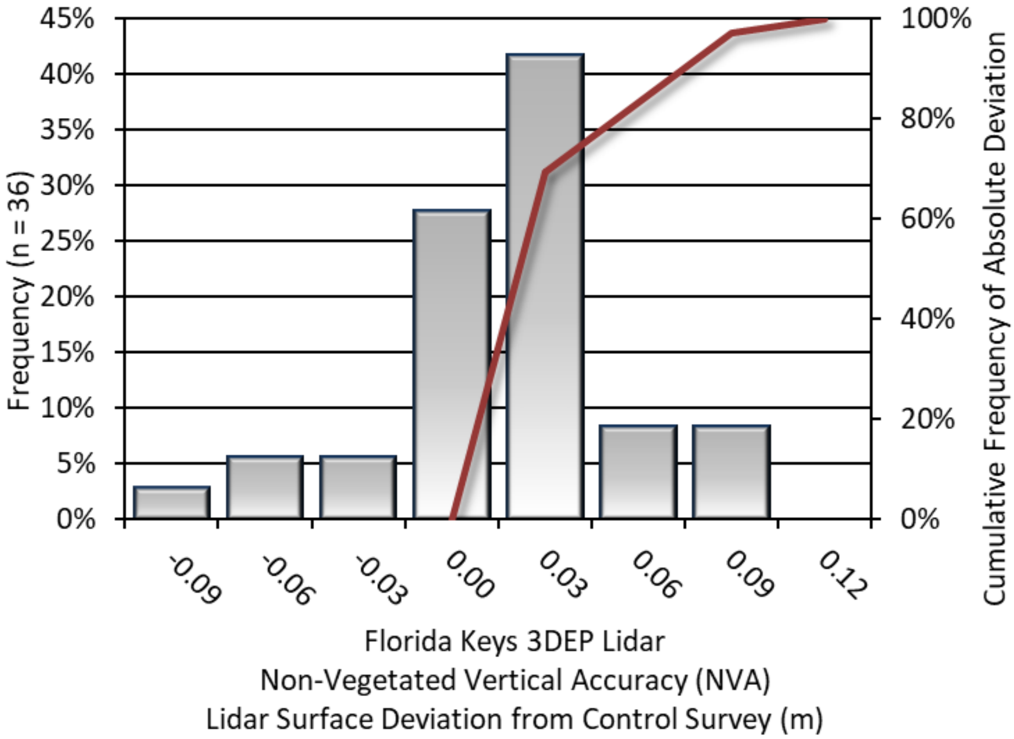

Figure 8: Frequency for lidar surface deviation from ground check point values

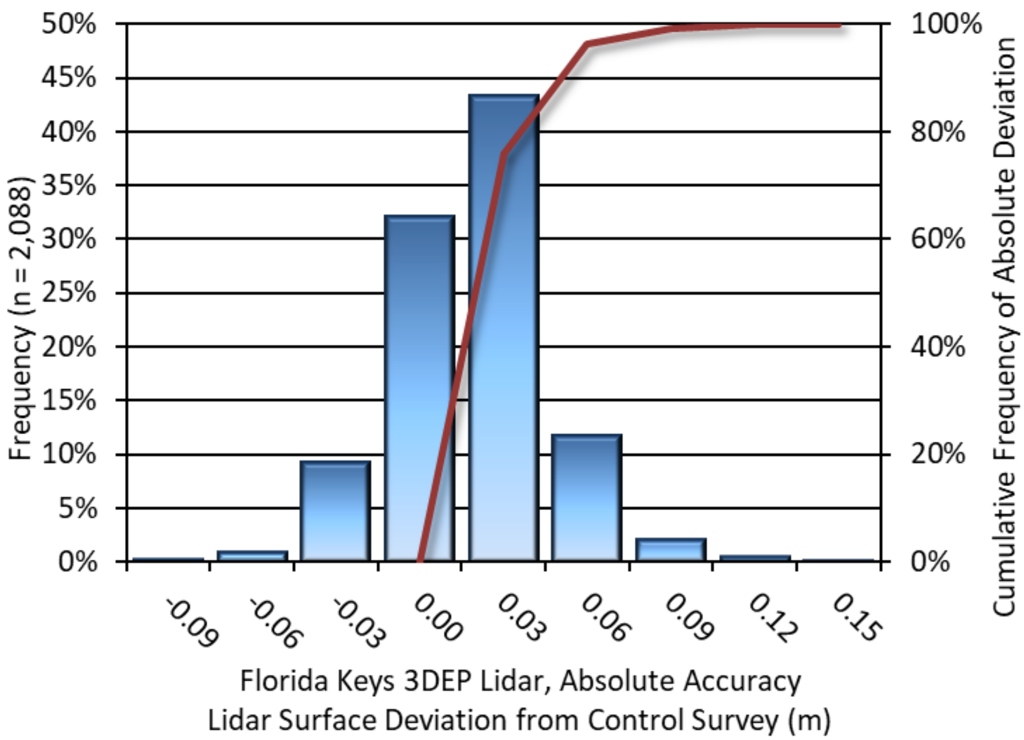

Figure 9: Frequency histogram for lidar surface deviation ground control point values

Lidar Vegetated Vertical Accuracies

NV5 Geospatial also assessed vertical accuracy using Vegetated Vertical Accuracy (VVA) reporting. VVA compares known ground check point data collected over vegetated surfaces using land class descriptions to the triangulated ground surface generated by the ground classified lidar points and to the ground classified LAS. VVA is evaluated at the 95th percentile (Table 14, Figure 10).

Table 14: Vegetated Vertical Accuracy for the Florida Keys 3DEP Lidar Project

Vegetated Vertical Accuracy (VVA)		
	VVA, as compared to classified LAS	**VVA, as compared to bare earth DEM**
Sample	23 points	23 points
95th Percentile	0.170 m	0.130 m
Average	0.068 m	0.063 m
Median	0.054 m	0.048 m
RMSE	0.091 m	0.085 m
Standard Deviation (1σ)	0.061 m	0.059 m

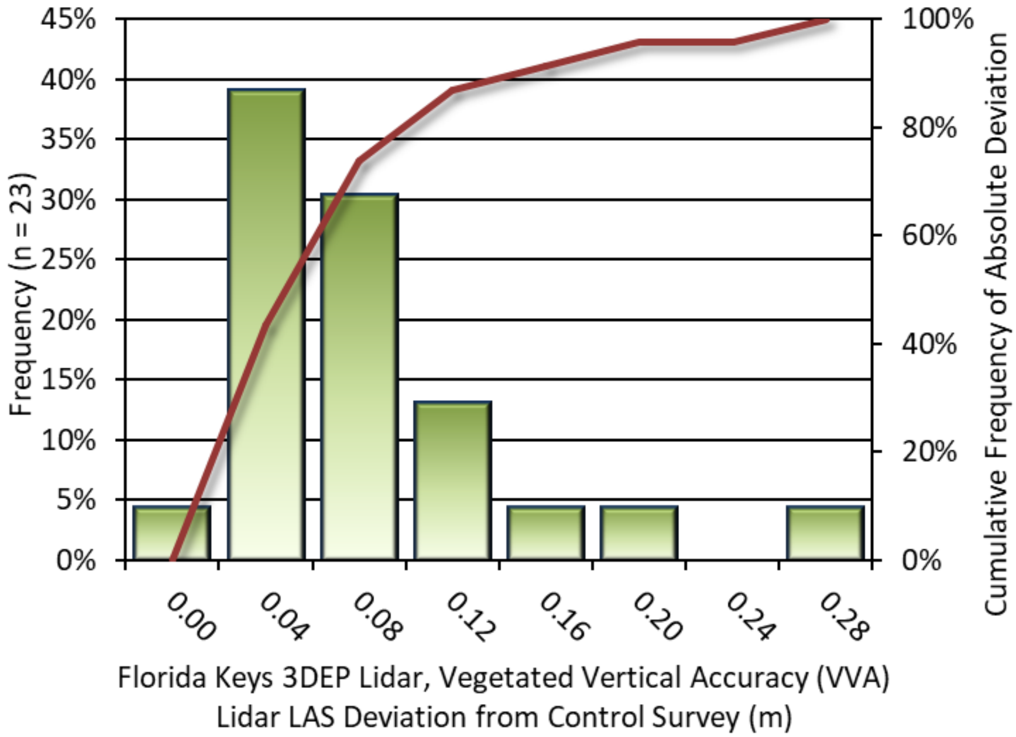

Figure 10: Frequency histogram for lidar classified LAS deviation from ground check point values (VVA)

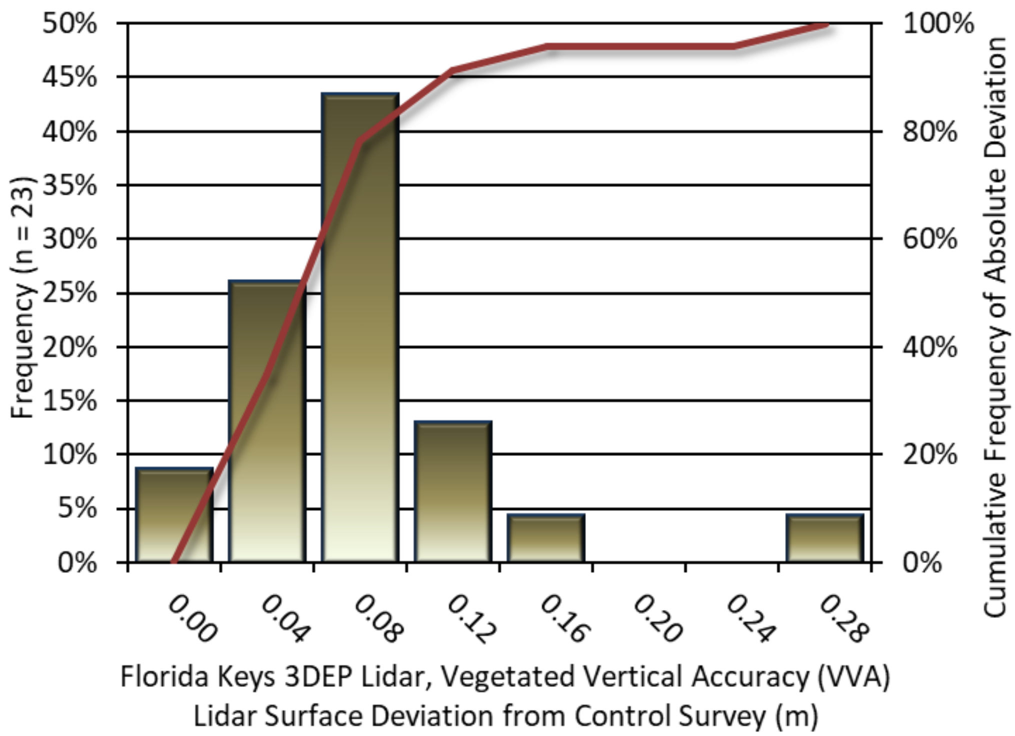

Figure 11: Frequency histogram for lidar surface deviation from all land cover class point values (VVA)

Lidar Relative Vertical Accuracy

Relative vertical accuracy refers to the internal consistency of the data set as a whole: the ability to place an object in the same location given multiple flight lines, GPS conditions, and aircraft attitudes. When the lidar system is well calibrated, the swath-to-swath vertical divergence is low (<0.10 meters). The relative vertical accuracy was computed by comparing the ground surface model of each individual flight line with its neighbors in overlapping regions. The average (mean) line to line relative vertical accuracy for the Florida Keys 3DEP Lidar project was 0.036 meters (Table 15, Figure 12).

Table 15: Relative accuracy results

Relative Accuracy	
Sample	1511 flight line surfaces
Average	0.036 m
Median	0.035 m
RMSE	0.047 m
Standard Deviation (1σ)	0.020 m
1.96σ	0.039 m

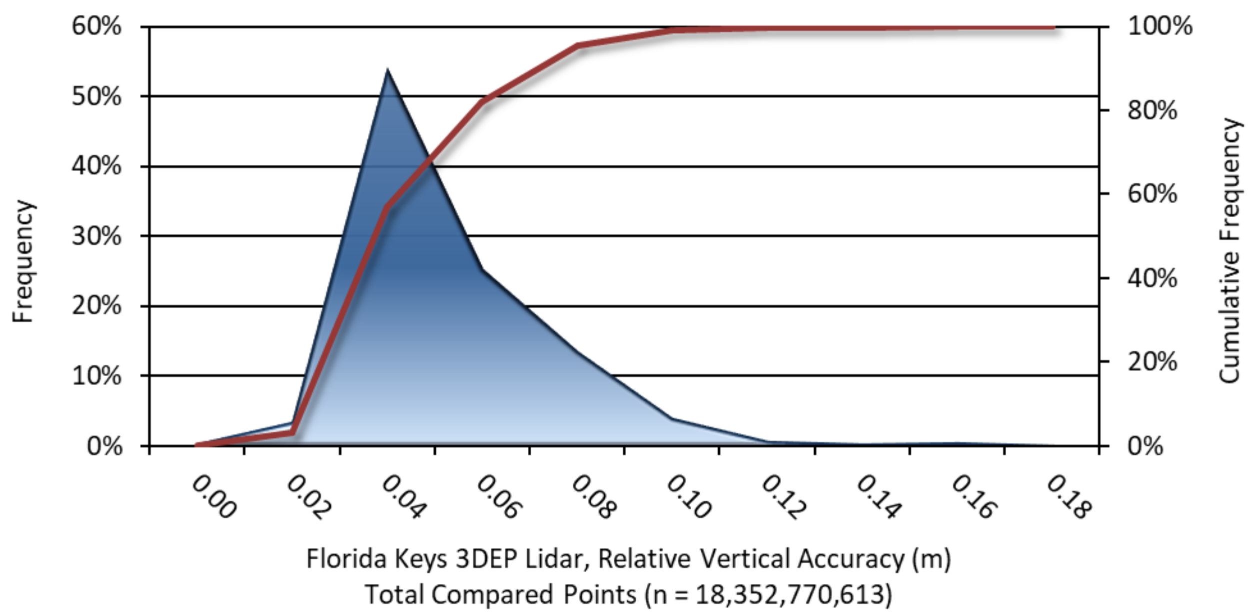

Figure 12: Frequency plot for relative vertical accuracy between flight lines

Lidar Horizontal Accuracy

Lidar horizontal accuracy is a function of Global Navigation Satellite System (GNSS) derived positional error, flying altitude, and INS derived attitude error. The obtained $RMSE_r$ value is multiplied by a conversion factor of 1.7308 to yield the horizontal component of the National Standards for Spatial Data Accuracy (NSSDA) reporting standard where a theoretical point will fall within the obtained radius 95 percent of the time. Based on a flying altitude of 400 meters, an IMU error of 0.005 decimal degrees, and a GNSS positional error of 0.023 meters, this project was compiled to meet 0.115 m horizontal accuracy at the 95% confidence level.

Table 16: Horizontal Accuracy

Horizontal Accuracy	
$RMSE_r$	0.067 m
ACC_r	0.115 m

NV5 Geospatial, Inc. provided lidar services for the Florida Keys 3DEP Lidar project as described in this report.

I, Steven Miller, have reviewed the attached report for completeness and hereby state that it is a complete and accurate report of this project.

Jan 4, 2021

Steven Miller
Project Manager
NV5 Geospatial, Inc.

I, Steven J. Hyde, PLS, being duly registered as a Professional Surveyor and Mapper in and by the state of Florida, hereby certify that the methodologies, static GNSS occupations used during airborne flights, and ground survey point collection were performed using commonly accepted Standard Practices. Field work conducted for this report was conducted between November 20, 2018 and October 23, 2019.

Accuracy statistics shown in the Accuracy Section of this Report have been reviewed by me and found to meet the "National Standard for Spatial Data Accuracy".

STEVEN J. HYDE
CERTIFICATE
No. 6436
STATE OF
FLORIDA
Registered Surveyor & Mapper
1/4/2021

Steven J. Hyde, PSM #6436
NV5 Geospatial, Inc.
St. Petersburg, FL

GLOSSARY

1-sigma (σ) Absolute Deviation: Value for which the data are within one standard deviation (approximately 68th percentile) of a normally distributed data set.

1.96 * RMSE Absolute Deviation: Value for which the data are within two standard deviations (approximately 95th percentile) of a normally distributed data set, based on the FGDC standards for Non-vegetated Vertical Accuracy (NVA) reporting.

Accuracy: The statistical comparison between known (surveyed) points and laser points. Typically measured as the standard deviation (sigma σ) and root mean square error (RMSE).

> **Absolute Accuracy:** The vertical accuracy of lidar data is described as the mean and standard deviation (sigma σ) of divergence of lidar point coordinates from ground survey point coordinates. To provide a sense of the model predictive power of the dataset, the root mean square error (RMSE) for vertical accuracy is also provided. These statistics assume the error distributions for x, y and z are normally distributed, and thus we also consider the skew and kurtosis of distributions when evaluating error statistics.
>
> **Relative Accuracy:** Relative accuracy refers to the internal consistency of the data set; i.e., the ability to place a laser point in the same location over multiple flight lines, GPS conditions and aircraft attitudes. Affected by system attitude offsets, scale and GPS/IMU drift, internal consistency is measured as the divergence between points from different flight lines within an overlapping area. Divergence is most apparent when flight lines are opposing. When the lidar system is well calibrated, the line-to-line divergence is low (<10 cm).
>
> **Root Mean Square Error (RMSE):** A statistic used to approximate the difference between real-world points and the lidar points. It is calculated by squaring all the values, then taking the average of the squares and taking the square root of the average.

Data Density: A common measure of lidar resolution, measured as points per square meter.

Digital Elevation Model (DEM): File or database made from surveyed points, containing elevation points over a contiguous area. Digital terrain models (DTM) and digital surface models (DSM) are types of DEMs. DTMs consist solely of the bare earth surface (ground points), while DSMs include information about all surfaces, including vegetation and man-made structures.

Intensity Values: The peak power ratio of the laser return to the emitted laser, calculated as a function of surface reflectivity.

Nadir: A single point or locus of points on the surface of the earth directly below a sensor as it progresses along its flight line.

Overlap: The area shared between flight lines, typically measured in percent. 100% overlap is essential to ensure complete coverage and reduce laser shadows.

Pulse Rate (PR): The rate at which laser pulses are emitted from the sensor; typically measured in thousands of pulses per second (kHz).

Pulse Returns: For every laser pulse emitted, the number of wave forms (i.e., echoes) reflected back to the sensor. Portions of the wave form that return first are the highest element in multi-tiered surfaces such as vegetation. Portions of the wave form that return last are the lowest element in multi-tiered surfaces.

Real-Time Kinematic (RTK) Survey: A type of surveying conducted with a GPS base station deployed over a known monument with a radio connection to a GPS rover. Both the base station and rover receive differential GPS data and the baseline correction is solved between the two. This type of ground survey is accurate to 1.5 cm or less.

Post-Processed Kinematic (PPK) Survey: GPS surveying is conducted with a GPS rover collecting concurrently with a GPS base station set up over a known monument. Differential corrections and precisions for the GNSS baselines are computed and applied after the fact during processing. This type of ground survey is accurate to 1.5 cm or less.

Scan Angle: The angle from nadir to the edge of the scan, measured in degrees. Laser point accuracy typically decreases as scan angles increase.

Native Lidar Density: The number of pulses emitted by the lidar system, commonly expressed as pulses per square meter.

Relative Accuracy Calibration Methodology:

Manual System Calibration: Calibration procedures for each mission require solving geometric relationships that relate measured swath-to-swath deviations to misalignments of system attitude parameters. Corrected scale, pitch, roll and heading offsets were calculated and applied to resolve misalignments. The raw divergence between lines was computed after the manual calibration was completed and reported for each survey area.

Automated Attitude Calibration: All data were tested and calibrated using TerraMatch automated sampling routines. Ground points were classified for each individual flight line and used for line-to-line testing. System misalignment offsets (pitch, roll and heading) and scale were solved for each individual mission and applied to respective mission datasets. The data from each mission were then blended when imported together to form the entire area of interest.

Automated Z Calibration: Ground points per line were used to calculate the vertical divergence between lines caused by vertical GPS drift. Automated Z calibration was the final step employed for relative accuracy calibration.

Lidar accuracy error sources and solutions:

Type of Error	Source	Post Processing Solution
GPS (Static/Kinematic)	Long Base Lines	None
	Poor Satellite Constellation	None
	Poor Antenna Visibility	Reduce Visibility Mask
Relative Accuracy	Poor System Calibration	Recalibrate IMU and sensor offsets/settings
	Inaccurate System	None
Laser Noise	Poor Laser Timing	None
	Poor Laser Reception	None
	Poor Laser Power	None
	Irregular Laser Shape	None

Operational measures taken to improve relative accuracy:

Low Flight Altitude: Terrain following was employed to maintain a constant above ground level (AGL). Laser horizontal errors are a function of flight altitude above ground (about 1/3000th AGL flight altitude).

Focus Laser Power at narrow beam footprint: A laser return must be received by the system above a power threshold to accurately record a measurement. The strength of the laser return (i.e., intensity) is a function of laser emission power, laser footprint, flight altitude and the reflectivity of the target. While surface reflectivity cannot be controlled, laser power can be increased and low flight altitudes can be maintained.

Reduced Scan Angle: Edge-of-scan data can become inaccurate. The scan angle was reduced to a maximum of ±29.25^{o} from nadir, creating a narrow swath width and greatly reducing laser shadows from trees and buildings.

Quality GPS: Flights took place during optimal GPS conditions (e.g., 6 or more satellites and PDOP [Position Dilution of Precision] less than 3.0). Before each flight, the PDOP was determined for the survey day. During all flight times, a dual frequency DGPS base station recording at 1 second epochs was utilized and a maximum baseline length between the aircraft and the control points was less than 13 nm at all times.

Ground Survey: Ground survey point accuracy (<1.5 cm RMSE) occurs during optimal PDOP ranges and targets a minimal baseline distance of 4 miles between GPS rover and base. Robust statistics are, in part, a function of sample size (n) and distribution. Ground survey points are distributed to the extent possible throughout multiple flight lines and across the survey area.

50% Side-Lap (100% Overlap): Overlapping areas are optimized for relative accuracy testing. Laser shadowing is minimized to help increase target acquisition from multiple scan angles. Ideally, with a 50% side-lap, the nadir portion of one flight line coincides with the swath edge portion of overlapping flight lines. A minimum of 50% side-lap with terrain-followed acquisition prevents data gaps.

Opposing Flight Lines: All overlapping flight lines have opposing directions. Pitch, roll and heading errors are amplified by a factor of two relative to the adjacent flight line(s), making misalignments easier to detect and resolve.