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PR USVI 2018 Lidar

Report Produced for U.S. Geological Survey

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Dewberry

Executive Summary

The primary purpose of this project was to support disaster recovery efforts required due to impacts from Hurricane Maria by developing a consistent and accurate surface elevation dataset derived from high-accuracy Light Detection and Ranging (lidar) technology for Puerto Rico and the U.S. Virgin Islands.

The lidar data were processed and classified according to project specifications. Detailed breaklines and bare-earth Digital Elevation Models (DEMs) were produced for the project area. Data was formatted according to tiles with each tile covering an area of 1500m by 1500m. A total of 4,675 tiles were produced for the project encompassing an area of approximately 3,587 sq. miles.

THE PROJECT TEAM

Dewberry served as the prime contractor for the project. In addition to project management, Dewberry was responsible for LAS classification, all lidar products, breakline production, Digital Elevation Model (DEM) production, and quality assurance.

Dewberry's Gary D. Simpson completed ground surveying for the project and delivered surveyed checkpoints. His task was to acquire surveyed checkpoints for the project to use in independent testing of the vertical accuracy of the lidar-derived surface model. He also verified the GPS base station coordinates used during lidar data acquisition to ensure that the base station coordinates were accurate. Please see Appendix A to view the separate Survey Report that was created for this portion of the project.

Leading Edge Geomatics completed lidar data acquisition and data calibration for the project area.

SURVEY AREA

As part of this project, locations within Puerto Rico and the US Virgin Islands were surveyed in order to collect 232 Check Points and 124 Ground Control Points for accuracy testing. Images have been provided below to detail where surveys were conducted as part of this effort.

DATE OF SURVEY

The Check Point and Ground Control Point surveys were conducted between July 5th, 2018 and August 15th, 2018.

COORDINATE REFERENCE SYSTEM

Data produced for the project were delivered in the following reference system.

Horizontal Datum: The horizontal datum for the project is North American Datum of 1983 with the 2011 Adjustment (NAD 83 (2011))
Vertical Datum: The Vertical datums for the project are Puerto Rico Vertical Datum 2002 and Virgin Islands Vertical Datum 2009
Coordinate System: State Plane Coordinate System, Puerto Rico USVI Zone 5200
Units: Horizontal units are in meters, Vertical units are in meters.
Geiod Model: Geoid12B (Geoid 12B was used to convert ellipsoid heights to orthometric heights).

LIDAR VERTICAL ACCURACY

For the island of Puerto Rico and its surrounding islands, the tested $RMSE_z$ of the classified lidar data for checkpoints in non-vegetated terrain equaled 6.8 cm compared with the 10 cm specification; and the NVA of the classified lidar data computed using $RMSE_z$ x 1.9600 was equal to 13.2 cm, compared with the 19.6 cm specification.

For the island of Puerto Rico and its surrounding islands, the tested VVA of the classified lidar data computed using the 95th percentile was equal to 27.0 cm, compared with the 29.4 cm specification.

For St. Croix, the tested $RMSE_z$ of the classified lidar data for checkpoints in non-vegetated terrain equaled 6.6 cm compared with the 10 cm specification; and the NVA of the classified lidar data computed using $RMSE_z$ x 1.9600 was equal to 12.9 cm, compared with the 19.6 cm specification.

For St. Croix, the tested VVA of the classified lidar data computed using the 95th percentile was equal to 9.5 cm, compared with the 29.4 cm specification.

For St. John and St. Thomas, the tested $RMSE_z$ of the classified lidar data for checkpoints in non-vegetated terrain equaled 5.2 cm compared with the 10 cm specification; and the NVA of the classified lidar data computed using $RMSE_z$ x 1.9600 was equal to 10.2 cm, compared with the 19.6 cm specification.

For St. John and St. Thomas, the tested VVA of the classified lidar data computed using the 95th percentile was equal to 11.1 cm, compared with the 29.4 cm specification.

Additional accuracy information and statistics for the classified lidar data, raw swath data, and bare earth DEM data are found in the following sections of this report.

PROJECT DELIVERABLES

The deliverables for this project are listed below.

1. Classified Point Cloud Data (Tiled)
2. Bare Earth Surface (Raster DEM – IMG Format)
3. Intensity Images (8-bit gray scale, tiled, GeoTIFF format)
4. Breakline Data (File GDB)
5. Independent Survey Checkpoint Data (Report, Photos, & Points)
6. Calibration Points
7. Metadata (XML files)
8. Project Report (Acquisition, Processing, QC)
9. Project Extents, Including a shapefile derived from the lidar deliverable
10. Flight Lines (GDB)
11. Interswath and Intraswath Data (shapefiles)

PROJECT TILING FOOTPRINT

Four thousand six hundred seventy five (4,675) tiles were delivered for the project. Each tile's extent is 1,500 meters by 1,500 meters (see Appendix C for a complete listing of delivered tiles).

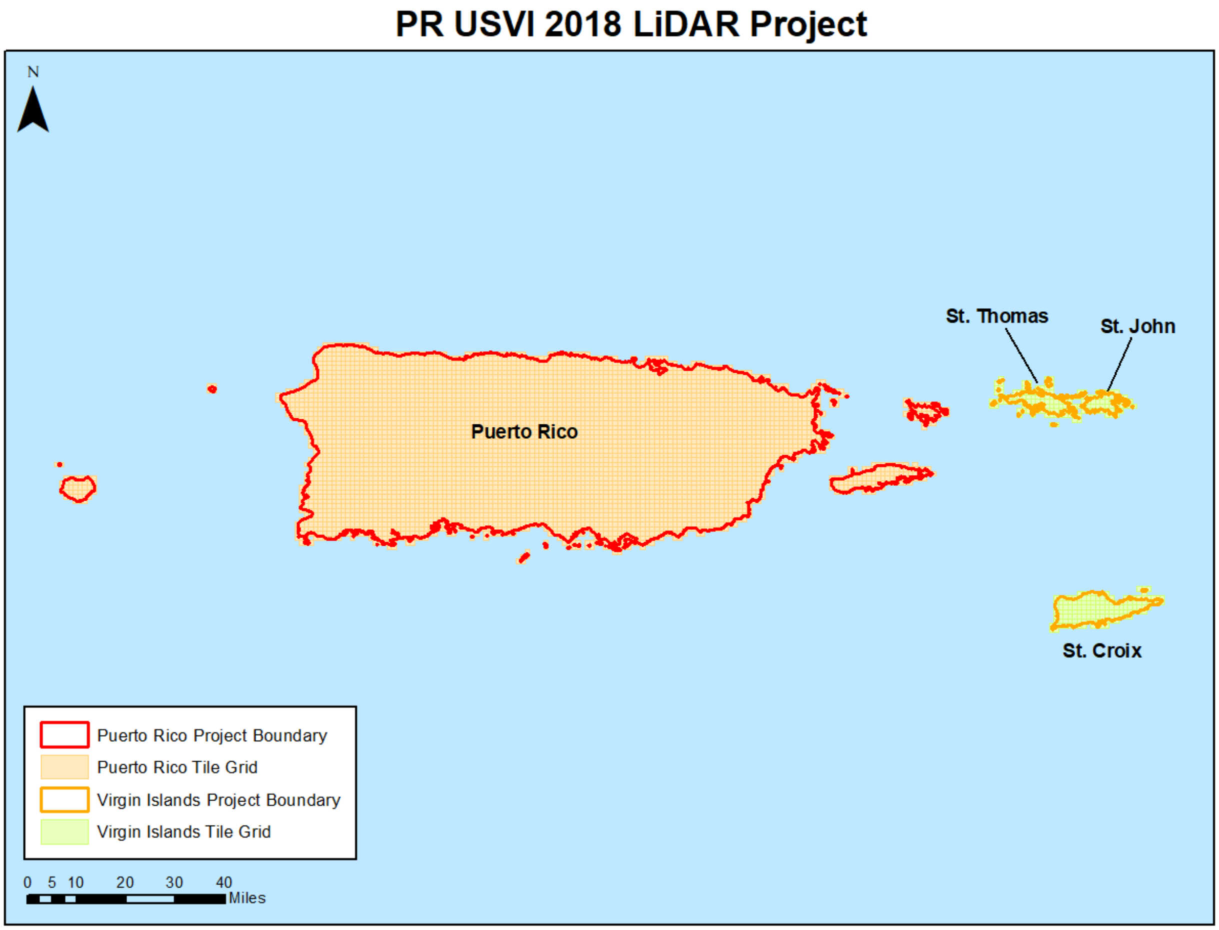


Figure 1 - Project Map

Lidar Acquisition Report

Dewberry elected to subcontract the lidar acquisition and calibration activities to Leading Edge Geomatics. Leading Edge Geomatics was responsible for providing lidar acquisition, calibration and delivery of lidar data files to Dewberry.

Dewberry received calibrated swath data from Leading Edge Geomatics from April 17, 2018 through April 18, 2019.

LIDAR ACQUISITION DETAILS

Leading Edge Geomatics planned 2,296 passes for the project area as a series of parallel flight lines with cross flight lines for the purposes of quality control. The flight plan included zigzag flight line collection as a result of the inherent IMU drift associated with all IMU systems. In order to reduce any margin for error in the flight plan, Leading Edge Geomatics followed FEMA's Appendix A "guidelines" for flight planning and, at a minimum, includes the following criteria:

- A digital flight line layout using Track Air 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 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, Leading Edge Geomatics will file our flight plans as required by local Air Traffic Control (ATC) prior to each mission.

Leading Edge Geomatics 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. Leading Edge Geomatics accesses reliable weather sites and indicators (webcams) to establish the highest probability for successful collection in order to position our sensor to maximize successful data acquisition.

Within 72-hours prior to the planned day(s) of acquisition, Leading Edge Geomatics 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.

Leading Edge Geomatics' LiDAR sensors are calibrated at a designated site located in downtown Fredericton, New Brunswick and are periodically checked and adjusted to minimize corrections at project sites. All systems were calibrated before departing for the project area. LEG also completed calibrations over San Juan, Puerto Rico.

LIDAR SYSTEM PARAMETERS

Leading Edge Geomatics operated multiple aircraft during the collection of the project area. A Piper PA-23 (Tail #45A), Cessna 206 (Tail# RBV), and Cessna 206 (Tail# XSS) were outfitted with either a Riegl VQ-1560i or Riegl LMS-Q1560 lidar system. A Riegl VQ-880-GII topobathy system was also used to refly a small portion of lidar on Puerto Rico's west coast. This airborne survey required that the lidar systems be programmed with different parameters for each mission area illustrated in Figure 2 to accommodate this geography's dynamic land cover. Table 1 through Table 4 list Leading Edge Geomatics' system parameters for the Riegl VQ-1560i, LMS-1560, and VQ-880-GII lidar systems.

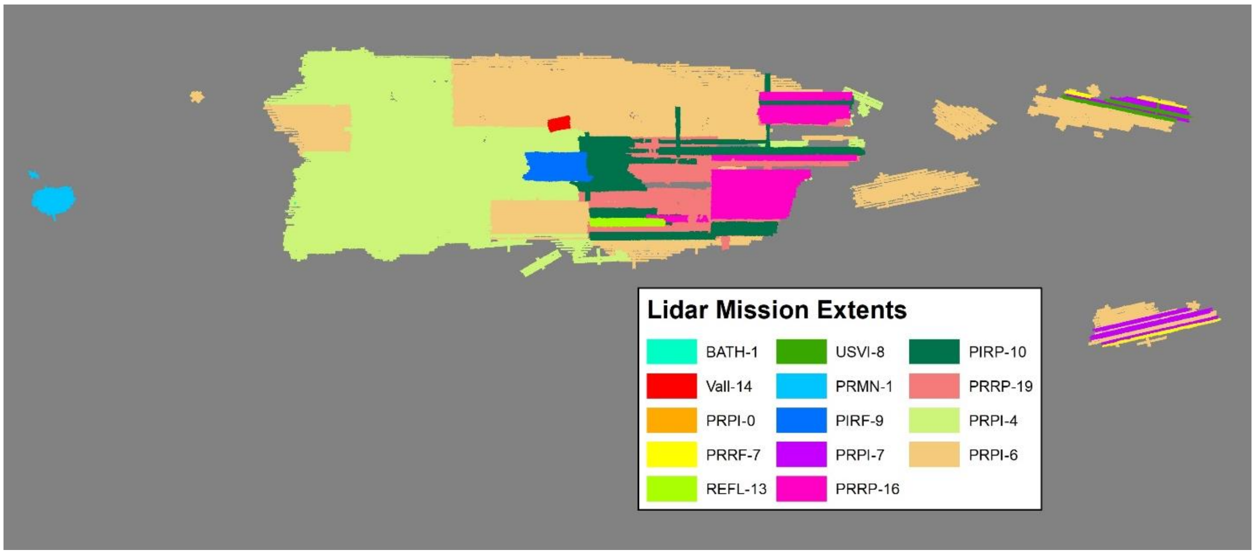


Figure 2 - Lidar Missions flown by Leading Edge Geomatics. Missions correspond with system parameters listed in Tables 1 through 4.

Plan	PRMN-1	PRPI-4	PRPI-6	PRPI-7
System	VQ1560i	VQ1560i	VQ1560i	VQ1560i
Maximum Number of Returns per Pulse	infinite	infinite	infinite	infinite
Nominal Pulse Spacing (m)	0.2	0.28	0.24	0.2
Nominal Pulse Density (ppsm)	25.5	12.5	17.3	25.5
Aggregate Nominal Pulse Spacing (m)	0.2	0.28	0.17	0.2
Aggregate Nominal Pulse Density (ppsm)	25.5	12.5	34.6	25.5
Altitude Aboge Ground Level (m)	700	1000	1000	700
Ground Speed (kts)	130	130	130	130
Total Sensor Scan Angle (degrees)	58	58	58	58
Scan Frequency / Lines per Second (Hz)	235	167	195	235
Scan Pulse Rate (kHz)	2x1000	2x700	2x1000	2x1000
Pulse Duration (ns)	3	3	3	3
Pulse Width (m)	0.8994	0.8994	0.8994	0.8994
Central Wavelength (nanometers)	1064	1064	1064	1064
Multiple Pulses in the Air	Yes	Yes	Yes	Yes
Beam Divergence (milliradians)	<=0.25	<=0.25	<=0.25	<=0.25

Nominal Swath Width on the Ground (m)	780	1110	1110	780
Swath Overlap (%)	0.2	0.2	0.55	0.3
Computed Down Track spacing per beam (m)	0.28	0.4	0.34	0.28
Computed Cross Track Spacing per beam (m)	0.28	0.4	0.34	0.28
GNSS positional error (radial, in cm)	2 (h), 5 (v)	2 (h), 5 (v)	2 (h), 5 (v)	2 (h), 5 (v)
IMU error (degrees)	0.0025 (r, p) 0.005 (y)	0.0025 (r, p) 0.005 (y)	0.0025 (r, p) 0.005 (y)	0.0025 (r, p) 0.005 (y)
Maximum Baseline Length (miles)	44	44	44	44
Line Spacing (m)	624	888	499.5	546

Table 1 - Leading Edge Geomatics lidar system parameters

Plan	**PRRF-7**	**USVIRF-8**	**USVIRF-8**	**PIRF-9**
System	VQ1560i	VQ1560i	VQ1560i	LMS-Q1560
Maximum Number of Returns per Pulse	infinite	infinite	infinite	infinite
Nominal Pulse Spacing (m)	0.2	0.15	0.17	0.28
Nominal Pulse Density (ppsm)	25.5	45.4	34.7	12.5
Aggregate Nominal Pulse Spacing (m)	0.2	0.15	0.17	0.2
Aggregate Nominal Pulse Density (ppsm)	25.5	45.4	34.7	25
Altitude Aboge Ground Level (m)	700	400	500	700
Ground Speed (kts)	130	130	130	100
Total Sensor Scan Angle (degrees)	58	58	58	58
Scan Frequencey / Lines per Second (Hz)	235	315	280	130
Scan Pulse Rate (kHz)	2x1000	2x1000	2x1000	2x400
Pulse Duration (ns)	3	3	3	3
Pulse Width (m)	0.8994	0.8994	0.8994	0.8994
Central Wavelength (nanometers)	1064	1064	1064	1064
Multiple Pulses in the Air	Yes	Yes	Yes	Yes
Beam Divergence (milliradians)	<=0.25	<=0.25	<=0.25	<=0.25
Nominal Swath Width on the Ground (m)	780	440	550	780
Swath Overlap (%)	0.3	0.2	0.2	0.55
Computed Down Track spacing per beam (m)	0.28	0.21	0.24	0.4
Computed Cross Track Spacing per beam (m)	0.28	0.21	0.24	0.4
GNSS positional error (radial, in cm)	2 (h), 5 (v)	2 (h), 5 (v)	2 (h), 5 (v)	5 (h), 10 (v)
IMU error (degrees)	0.0025 (r, p) 0.005 (y)	0.0025 (r, p) 0.005 (y)	0.0025 (r, p) 0.005 (y)	0.0050 (r, p) 0.008 (y)
Maximum Baseline Length (miles)	44	44	44	44
Line Spacing (m)	546	352	440	351

Table 2 - Leading Edge Geomatics lidar system parameters

Plan	PIRP-10	PIRP-10	PIRP-10	REFLY-13
System	LMS-Q1560	LMS-Q1560	LMS-Q1560	LMS-Q1560
Maximum Number of Returns per Pulse	infinite	infinite	infinite	infinite
Nominal Pulse Spacing (m)	0.31	0.32	0.35	0.32
Nominal Pulse Density (ppsm)	10.3	9.5	8.3	9.5
Aggregate Nominal Pulse Spacing (m)	0.22	0.23	0.25	0.23
Aggregate Nominal Pulse Density (ppsm)	20.6	19	16.6	19
Altitude Aboge Ground Level (m)	700	800	900	800
Ground Speed (kts)	120	120	120	120
Total Sensor Scan Angle (degrees)	58	58	58	58
Scan Frequency / Lines per Second (Hz)	140	135	125	135
Scan Pulse Rate (kHz)	2x400	2x400	2x400	2x400
Pulse Duration (ns)	3	3	3	3
Pulse Width (m)	0.8994	0.8994	0.8994	0.8994
Central Wavelength (nanometers)	1064	1064	1064	1064
Multiple Pulses in the Air	Yes	Yes	Yes	Yes
Beam Divergence (milliradians)	<=0.25	<=0.25	<=0.25	<=0.25
Nominal Swath Width on the Ground (m)	780	890	1000	890
Swath Overlap (%)	0.5	0.5	0.5	0.5
Computed Down Track spacing per beam (m)	0.44	0.46	0.49	0.46
Computed Cross Track Spacing per beam (m)	0.44	0.46	0.49	0.46
GNSS positional error (radial, in cm)	5 (h), 10 (v)	5 (h), 10 (v)	5 (h), 10 (v)	5 (h), 10 (v)
IMU error (degrees)	0.0050 (r, p) 0.008 (y)	0.0050 (r, p) 0.008 (y)	0.0050 (r, p) 0.008 (y)	0.0050 (r, p) 0.008 (y)
Maximum Baseline Length (miles)	44	44	44	44
Line Spacing (m)	390	445	500	445

Table 3 - Leading Edge Geomatics lidar system parameters

Plan	VALLEY-14	PRRP-16	PRRP-19	BATHY-1
System	LMS-Q1560	LMS-Q1560	LMS-Q1560	VQ-880G
Maximum Number of Returns per Pulse	infinite	infinite	infinite	infinite
Nominal Pulse Spacing (m)	0.34	0.53	0.71	0.82
Nominal Pulse Density (ppsm)	8.7	3.6	2	1.5
Aggregate Nominal Pulse Spacing (m)	0.24	0.37	0.71	0.82
Aggregate Nominal Pulse Density (ppsm)	17.4	7.2	2	1.5
Altitude Aboge Ground Level (m)	900	1600	1900	450
Ground Speed (kts)	120	120	120	130
Total Sensor Scan Angle (degrees)	58	58	58	40

Scan Frequencey / Lines per Second (Hz)	125	82	62	80
Scan Pulse Rate (kHz)	2x400	2x300	2x200	200
Pulse Duration (ns)	3	3	3	3
Pulse Width (m)	0.8994	0.8994	0.8994	0.45
Central Wavelength (nanometers)	1064	1064	1064	1064
Multiple Pulses in the Air	Yes	Yes	Yes	Yes
Beam Divergence (milliradians)	<=0.25	<=0.25	<=0.25	0.2
Nominal Swath Width on the Ground (m)	1000	1770	2110	327
Swath Overlap (%)	0.55	0.55	0.3	20
Computed Down Track spacing per beam (m)	0.48	0.75	1	0.452
Computed Cross Track Spacing per beam (m)	0.48	0.75	1	0.452
GNSS positional error (radial, in cm)	5 (h), 10 (v)	5 (h), 10 (v)	5 (h), 10 (v)	5 (h), 10 (v
IMU error (degrees)	0.0050 (r, p) 0.008 (y)	0.0050 (r, p) 0.008 (y)	0.0050 (r, p) 0.008 (y)	.0050 (r, p)
Maximum Baseline Length (miles)	44	44	44	25
Line Spacing (m)	450	796.5	1477	261

Table 4 - Leading Edge Geomatics lidar system parameters

ACQUISITION STATUS REPORT AND FLIGHTLINES

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 impacted by unfavorable conditions were marked as invalid and re-flown immediately or at an optimal time.

Figure 2 shows the combined trajectory of the flightlines.

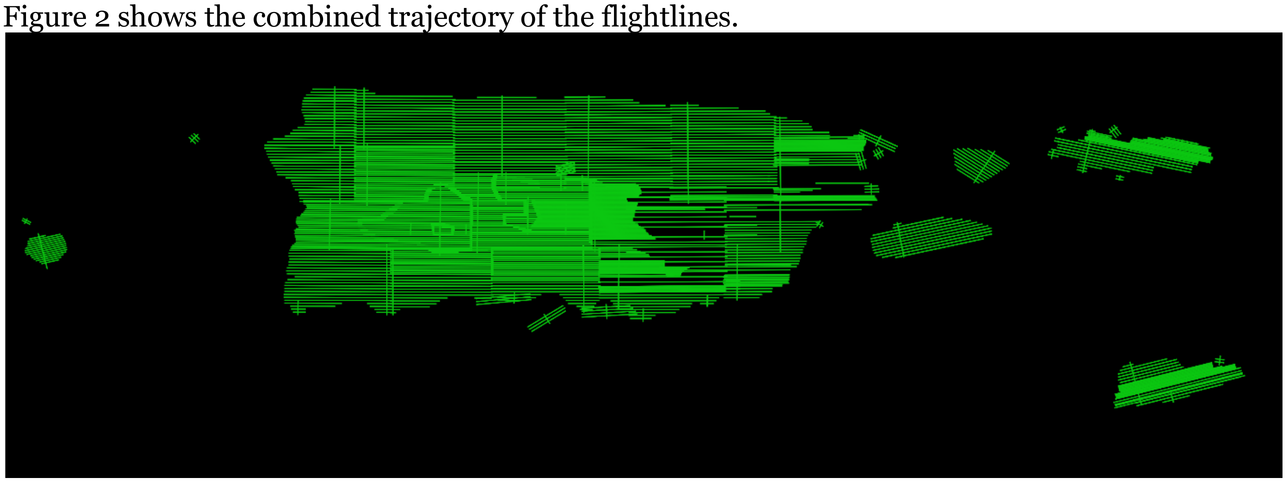


Figure 3 - Trajectories as flown by Leading Edge Geomatics

LIDAR CONTROL

Twelve (12) CORS and one (1) independent (Mona 2018) base stations were used to control the lidar acquisition for the project area. The coordinates of all base stations used for this project are provided in the table below. All control and calibration points are also provided in shapefile format as part of the final deliverables.

Name	NAD83(2011) UTM 18N		Ellipsoid Ht (NAD83(2011), m)	Orthometric Ht (NAVD88 Geoid12B, m)
	Easting X (m)	Northing Y (m)		
CRO1	396090.9383	192289.2548	-29.423	11.845
PRAR	177385.6711	268820.5608	-18.543	25.034
PRFJ	282659.491	254225.9129	-20.768	20.608
PRGY	159651.9386	224576.1748	35.760	75.081
PRHL	229566.6991	259606.2118	-22.539	18.656
PRJC	140156.0841	255986.5955	24.727	66.361
PRLP	259779.3706	239383.8986	58.883	98.661
PRLT	119982.1208	224699.3212	-13.360	26.633
PRMI	135171.4506	215388.4042	-23.594	16.297
PRN4	206801.4503	226380.1013	131.067	169.724
VITH	354756.8144	256512.7618	6.380	48.572
1 - Base (Mona 2018)	40285.41266	228881.5315	-39.358	2.606
ZSU4	246470.8237	265173.6742	-26.670	15.539

Table 5 – Base stations used to control lidar acquisition

AIRBORNE GPS KINEMATIC

Airborne GPS data was processed using the PosPac kinematic On-The-Fly (OTF) software suite. Flights were flown with a minimum of 6 satellites in view (13° above the horizon) and with a PDOP of better than 4. Distances from base station to aircraft were kept to a maximum of 70 km.

For all flights, the GPS data can be classified as excellent, with GPS residuals of 3 cm average or better but no larger than 10 cm being recorded.

GPS processing reports for each mission are included in Appendix D.

GENERATION AND CALIBRATION OF LASER POINTS (RAW DATA)

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.

Subsequently the mission points are output using Riegl RiProcess, initially with default values from Riegl or the last mission calibrated for the system. The initial point generation for each mission calibration is verified within QGIS and LP360 for calibration errors. If a calibration error greater than specification is observed within the mission, the roll, pitch and scanner scale corrections that need to be applied are calculated using BayesMap StripAlign. The missions with the new calibration values are regenerated and validated internally once again to ensure quality.

Data collected by the lidar unit is reviewed for completeness, acceptable density and to make sure all data is captured without errors or corrupted values. In addition, all GPS, aircraft trajectory, mission information, and ground control files are reviewed and logged into a database.

On a project level, a supplementary coverage check is carried out to ensure no data voids unreported by Field Operations are present. During this acquisition campaign, cloud cover prevented acquisition of portions of the southeast shown in Figure 3. After repeated attempts to collect these areas and discussions with USGS, the decision was made to conclude the acquisition phase of this project.

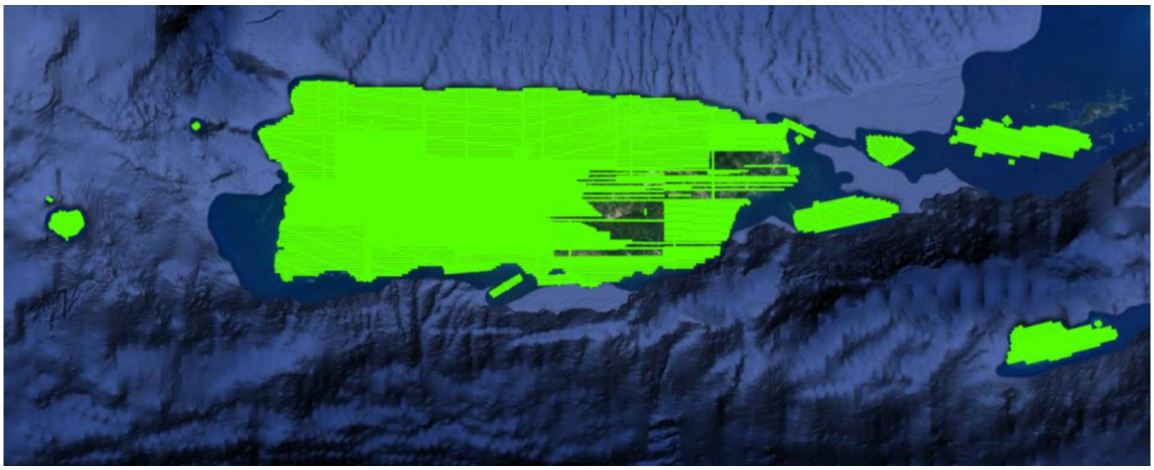


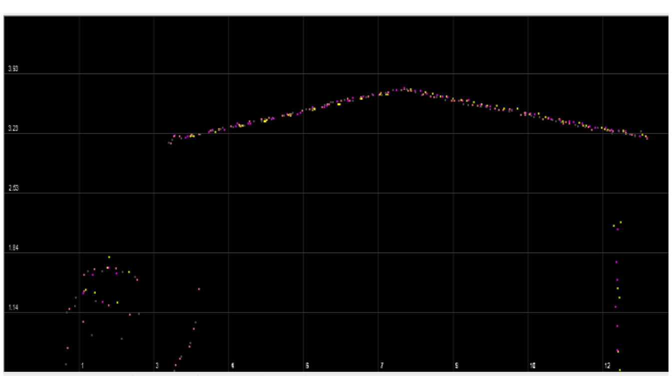
Figure 4 – Flight lines acquired for the PR-USVI 2018 project area.

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.

For this project the specifications used are as follows:
Relative accuracy <= 6 cm maximum differences within individual swaths and <=8 cm RMSDz between adjacent and overlapping swaths.



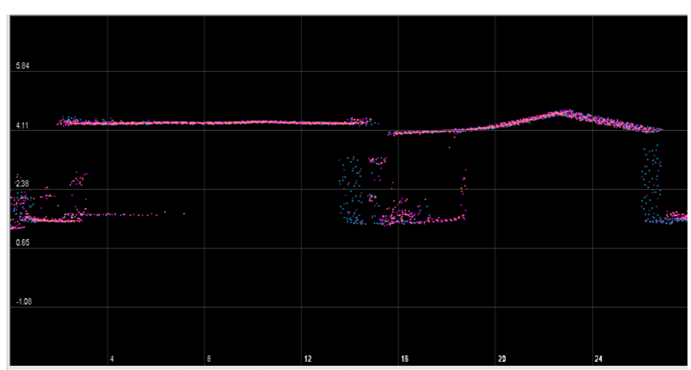


Figure 5 – Profile views showing correct roll and pitch adjustments for block E2.

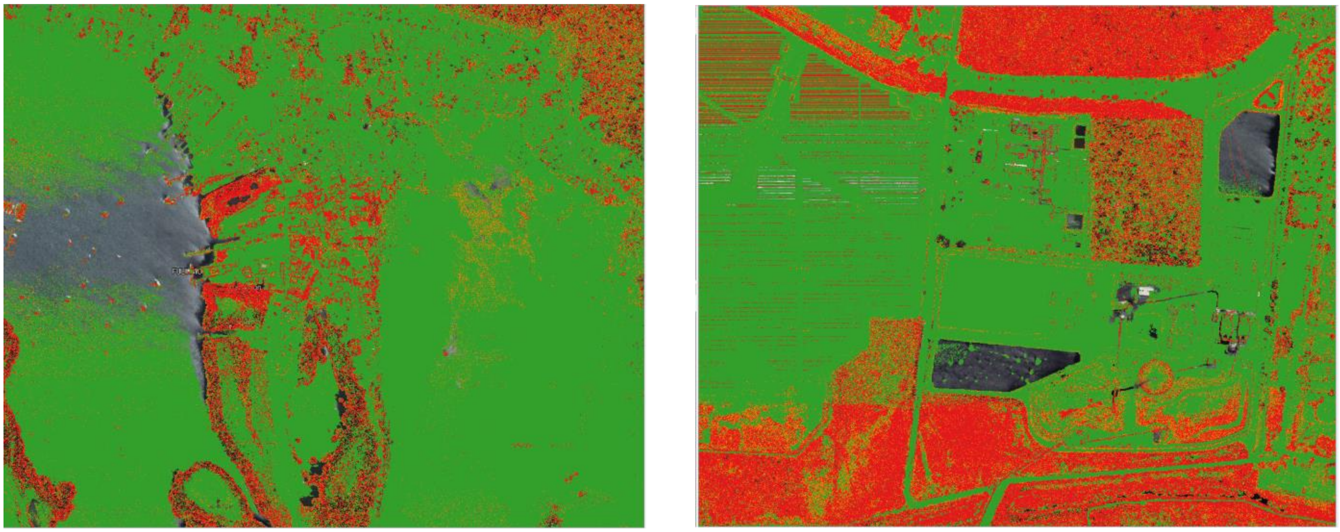


Figure 6 – QC block colored by distance to ensure accuracy at swath edges (interswath E2).

A different set of QC blocks are generated for final review after all transformations have been applied.

PRELIMINARY VERTICAL ACCURACY ASSESSMENT

A preliminary $RMSE_z$ error check is performed by Leading Edge Geomatics at this stage of the project life cycle in the raw lidar dataset against GPS static and kinematic data and compared to $RMSE_z$ project specifications. The lidar data is examined in non-vegetated, flat areas away from breaks. Lidar ground points for each flight line generated by an automatic classification routine are used.

Prior to delivery to Dewberry, the elevation data was verified internally to ensure it met Non-vegetated Vertical Accuracy (NVA) requirements ($RMSE_z \leq$ 10 cm and $Accuracy_z$ at the 95% confidence level ≤ 19.6 cm) when compared to static and kinematic GPS checkpoints. Below is a summary for the test:

The calibrated PR-USVI 2018 lidar dataset was tested to 0.17 m vertical accuracy at 95% confidence level based on $RMSE_z$ (0.087 m x 1.9600) when compared to 112 GPS static check points.

The following are the final statistics for the GPS static checkpoints used by Leading Edge Geomatics to internally verify vertical accuracy.

Point ID	NAD83(2011) UTM Zone 18N		NAVD88 (Geoid 12B)		DeltaZ
	Easting X (m)	Northing Y (m)	Z-Survey (m)	Z-LiDAR (m)	
GCP-003	265877.800	227800.100	53.180	53.330	0.150

GCP-004	242171.400	261028.200	63.780	63.760	-0.020
GCP-005	252438.500	252001.900	218.600	218.660	0.060
GCP-006	238100.800	252320.700	91.660	91.660	0.000
GCP-007	222186.800	263205.600	69.800	69.860	0.060
GCP-008	223111.900	252374.800	84.280	84.280	0.000
GCP-009	206512.400	255569.600	172.690	172.730	0.040
GCP-010	208994.400	271811.000	2.530	2.540	0.010
GCP-011	210922.600	264217.900	29.690	29.730	0.040
GCP-012	195369.900	252472.000	361.420	361.500	0.080
GCP-013	194481.100	261270.300	86.690	86.660	-0.030
GCP-014	194827.300	270480.700	26.030	26.100	0.070
GCP-015	182615.900	272376.600	6.660	6.810	0.150
GCP-016	181316.100	266441.100	100.050	100.000	-0.050
GCP-017	185217.800	258540.000	183.590	183.560	-0.030
GCP-018	170529.200	251618.500	214.840	214.880	0.040
GCP-019	171651.600	263890.000	13.320	13.230	-0.090
GCP-020	155337.300	272534.800	8.710	8.630	-0.080
GCP-021	155542.600	266422.400	159.780	159.540	-0.240
GCP-022	157050.100	261319.000	279.690	279.750	0.060
GCP-023	143847.400	259999.600	179.120	179.230	0.110
GCP-024	142502.200	267470.900	167.070	167.000	-0.070
GCP-025	139460.800	273828.400	63.310	63.340	0.030
GCP-027	129025.000	268316.000	146.360	146.350	-0.010
GCP-028	128107.800	262692.200	53.450	53.520	0.070
GCP-029	114517.000	254895.500	8.290	8.300	0.010
GCP-030	124337.800	254719.600	152.200	152.280	0.080
GCP-031	127733.100	249136.600	17.380	17.370	-0.010
GCP-032	128976.000	240608.600	115.400	115.470	0.070
GCP-033	142119.200	238755.800	426.460	426.620	0.160
GCP-034	123472.800	236604.000	4.070	4.080	0.010
GCP-035	136108.800	229047.600	45.570	45.570	0.000
GCP-036	128540.700	222515.500	29.450	29.460	0.010
GCP-037	120837.400	215143.300	0.830	0.810	-0.020
GCP-038	169117.100	225880.900	87.740	87.820	0.080
GCP-039	169440.100	218604.200	11.670	11.650	-0.020
GCP-040	192512.900	223278.600	45.460	45.520	0.060
GCP-041	207171.800	214921.100	3.540	3.620	0.080
GCP-042	220418.700	222614.000	83.230	83.270	0.040
GCP-043	256775.000	218853.800	10.180	10.220	0.040

GCP-044	256872.600	226797.100	22.330	22.420	0.090
GCP-045	262917.200	234586.200	29.380	29.420	0.040
GCP-046	267896.700	242498.600	19.860	19.880	0.020
GCP-047	270874.600	258977.500	17.470	17.560	0.090
GCP-048	284316.100	259103.500	5.370	5.440	0.070
GCP-049	229727.400	237909.400	409.820	409.820	0.000
GCP-050	219022.300	233996.900	614.460	614.560	0.100
GCP-051	204313.800	243727.000	507.350	507.440	0.090
GCP-052	169043.800	236507.000	480.670	480.770	0.100
GCP-053	259761.100	248169.900	476.300	476.420	0.120
GCP-054	229831.300	266962.500	3.800	3.890	0.090
GCP-055	261014.100	260204.300	15.150	15.280	0.130
GCP-056	241242.200	246855.600	65.520	65.530	0.010
GCP-057	260893.700	265981.300	3.110	3.040	-0.070
GCP-058	230197.000	257468.800	48.180	48.250	0.070
GCP-059	198784.300	266062.200	81.840	81.800	-0.040
GCP-060	165931.100	268341.000	77.540	77.560	0.020
GCP-061	166093.800	260113.300	236.570	236.680	0.110
GCP-062	136897.500	270176.300	128.100	128.090	-0.010
GCP-063	119004.400	260923.700	3.030	3.040	0.010
GCP-064	136720.900	258403.600	78.480	78.570	0.090
GCP-065	123169.700	242752.000	1.710	1.710	0.000
GCP-066	122411.600	229118.500	30.690	30.710	0.020
GCP-067	147109.700	214794.200	11.640	11.650	0.010
GCP-068	152846.900	225837.500	176.900	176.950	0.050
GCP-069	177063.700	217863.600	15.690	15.720	0.030
GCP-070	208899.400	228375.200	146.260	146.310	0.050
GCP-071	227833.700	213376.100	1.930	1.930	0.000
GCP-072	245925.500	217188.100	17.960	18.030	0.070
GCP-073	267922.500	229042.300	2.370	2.480	0.110
GCP-074	254806.100	238176.200	125.740	125.840	0.100
GCP-075	279360.000	243625.800	27.940	27.950	0.010
GCP-077	283344.900	255627.900	10.230	10.300	0.070
GCP-078	227262.200	229750.200	462.010	462.070	0.060
GCP-079	193329.900	232710.800	173.410	173.410	0.000
GCP-080	180968.800	242844.000	408.860	409.020	0.160
GCP-081	157481.000	238779.500	463.570	463.630	0.060
GCP-085	349655.000	258131.800	119.970	119.980	0.010
GCP-086	357955.800	256668.900	1.340	1.330	-0.010
GCP-087	367077.000	254637.500	23.690	23.830	0.140
GCP-088	364585.700	185393.900	16.530	16.510	-0.020
GCP-089	374708.300	191307.400	58.270	58.190	-0.080
GCP-090	388637.700	189535.000	7.880	7.760	-0.120

GCP-091	373388.900	255626.300	1.810	1.890	0.080
GCP-092	382416.900	253828.100	32.900	32.920	0.020
GCP-093	379491.200	259563.400	2.100	2.130	0.030
GCP-096	132899.100	228013.500	31.700	31.600	-0.100
GCP-097	141172.500	245865.600	307.270	307.320	0.050
GCP-098	131638.900	246510.700	79.540	79.640	0.100
GCP-099	133289.100	216410.800	23.400	23.380	-0.020
GCP-100	142285.100	221590.500	11.870	11.890	0.020
GCP-101	146068.300	254557.100	318.480	318.580	0.100
GCP-102	151701.500	250636.000	386.510	386.620	0.110
GCP-103	155581.500	248689.800	472.930	472.980	0.050
GCP-104	161954.800	242077.800	672.460	672.580	0.120
GCP-105	168176.200	231063.000	902.140	902.240	0.100
GCP-106	179050.800	235097.500	777.180	777.290	0.110
GCP-107	184021.800	252555.500	286.400	286.430	0.030
GCP-108	188412.200	268959.600	4.230	4.650	0.420
GCP-109	183762.400	223250.000	45.660	45.710	0.050
GCP-110	194741.800	217364.300	1.080	1.200	0.120
GCP-111	215226.900	244970.600	611.520	611.550	0.030
GCP-112	240308.700	240856.200	98.900	98.810	-0.090
GCP-113	247149.600	224570.900	449.390	449.480	0.090
GCP-114	253436.200	243647.300	82.850	82.930	0.080
GCP-115	246022.100	268150.900	2.050	2.150	0.100
GCP-116	261184.900	252531.700	512.100	512.230	0.130
GCP-118	357471.500	259191.800	148.260	148.260	0.000
GCP-119	365051.200	257490.900	3.430	3.490	0.060
GCP-120	377485.300	188867.600	27.720	27.780	0.060
GCP-122	238434.500	231282.700	765.850	766.020	0.170
GCP-123	148110.200	231288.200	651.170	651.200	0.030

Table 6 - Static GPS Points

100 % of Totals	# of Points	RMSEz (m) NVA Spec=0.1 m	NVA at 95% Spec=0.196 m	Mean (m)	Std Dev (m)	Min (m)	Max (m)
Non-Vegetated Terrain	112	0.087	0.17	0.043	0.075	-0.240	0.420

Table 7 - Static GPS Vertical Accuracy Results

Overall the calibrated lidar data products collected by Leading Edge Geomatics meet or exceed the requirements set out in the Statement of Work. The quality control requirements of Leading Edge Geomatics quality management program were adhered to throughout the acquisition stage for this project to ensure product quality.

Lidar Processing & Qualitative Assessment

INITIAL PROCESSING

Once Dewberry receives the calibrated swath data from the acquisition provider, Dewberry performs 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 Dewberry 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 overall schedule.

Final Swath Vertical Accuracy Assessment

Once Dewberry received the calibrated swath data from Leading Edge Geomatics, Dewberry tested the vertical accuracy of the non-vegetated terrain swath data prior to additional processing. Dewberry tested the vertical accuracy of the swath data using the ninety-one (91) 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. Dewberry typically uses LP360 software to test the swath lidar vertical accuracy, Terrascan software to test the classified lidar vertical accuracy, and Esri ArcMap to test the DEM vertical accuracy so that three 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 PR-USVI 2018 Lidar Project satisfies this criteria. The raw lidar swath dataset for the island of Puerto Rico and its surrounding islands 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 was found to be $RMSE_z$ = 7.5 cm, equating to +/- 15 cm at 95% confidence level. The table below shows all calculated statistics for the raw swath data.

100 % of Totals	# of Points	$RMSE_z$ NVA Spec=0.10 m	NVA –Non-vegetated Vertical Accuracy ($RMSE_z$ x 1.9600) Spec=0.196 m	Mean (m)	Median (m)	Skew	Std Dev (m)	Min (m)	Max (m)	Kurtosis
Non-Vegetated Terrain	91	0.075	0.148	0.053	0.060	-0.263	0.054	-0.090	0.190	0.413

Table 8 - NVA at 95% Confidence Level for the island of Puerto Rico and its surrounding islands Raw Swaths

Seven checkpoints were removed from the raw swath vertical accuracy testing. Five points were removed due to their locations underneath artifacts. Two points were removed due to being located in areas without any swath coverage. Only non-vegetated terrain checkpoints are used to test the raw swath data because the raw swath data has not been classified to remove vegetation, structures, and other above ground features from the ground classification. While these checkpoints are located in open terrain, the overhead artifacts are modeled by the lidar point cloud. These high points caused erroneous high values during the swath vertical accuracy testing so they were removed from the final calculations. Once the data underwent the classification process, the artifacts were removed from the final ground classification and these points could be used in the final vertical accuracy testing for the fully classified lidar data with the exception of the two checkpoints that were located in areas with no swath coverage. Table 9, below, provides the coordinates for these checkpoints and the vertical accuracy results from the raw swath data. Table 10, below, provides the usable vertical accuracy results of these checkpoints from the fully classified lidar. The differences in the tables show how above ground features can cause erroneous vertical accuracy results in the raw swath data.

Point ID	NAD83(2011) UTM Zone 18N		NAVD88 (Geoid 12B)	Lidar Z (m)	Delta Z	AbsDeltaZ
	Easting X (m)	Northing Y (m)	Survey Z (m)			
NVA-001	118857.830	216521.470	12.060	slope	N/A	N/A
NVA-023	134591.590	259403.720	75.370	slope	N/A	N/A
NVA-045	222240.000	242941.100	207.000	slope	N/A	N/A
NVA-053	192873.900	227103.500	74.030	slope	N/A	N/A
NVA-070	238317.580	232978.890	510.090	outside swath coverage	N/A	N/A
NVA-078	230745.750	245175.370	294.160	slope	N/A	N/A
NVA-083	268481.250	251871.410	642.910	outside swath coverage	N/A	N/A

Table 9 - Checkpoint removed from raw swath vertical accuracy testing

Point ID	NAD83(2011) UTM Zone 18N		NAVD88 (Geoid 12B)	Lidar Z (m)	Delta Z	AbsDeltaZ
	Easting X (m)	Northing Y (m)	Survey Z (m)			
NVA-001	118857.830	216521.470	12.060	12.040	-0.020	0.020
NVA-023	134591.590	259403.720	75.370	75.450	0.080	0.080
NVA-045	222240.000	242941.100	207.000	207.030	0.030	0.030
NVA-053	192873.900	227103.500	74.030	74.060	0.030	0.030
NVA-070	238317.580	232978.890	510.090	outside swath coverage	N/A	N/A
NVA-078	230745.750	245175.370	294.160	294.200	0.040	0.040
NVA-083	268481.250	251871.410	642.910	outside swath coverage	N/A	N/A

Table 10 - Final tested vertical accuracy for OT-130 post ground classification

The St. Croix raw lidar swath dataset 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 was found to be $RMSE_z$ = 7.2 cm, equating to +/- 14.2 cm at 95% confidence level. The table below shows all calculated statistics for the raw swath data.

100 % of Totals	# of Points	$RMSE_z$ NVA Spec=0.10 m	NVA –Non-vegetated Vertical Accuracy ($RMSE_z$ x 1.9600) Spec=0.196 m	Mean (m)	Median (m)	Skew	Std Dev (m)	Min (m)	Max (m)	Kurtosis
Non-Vegetated Terrain	22	0.072	0.142	0.030	0.023	0.255	0.067	-0.091	0.188	0.326

Table 11 - NVA at 95% Confidence Level for St. Croix Raw Swaths

The St. John and St. Thomas raw lidar swath dataset 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 was found to be $RMSE_z$ = 6.8 cm, equating to +/- 13.4 cm at 95% confidence level. The table below shows all calculated statistics for the raw swath data.

100 % of Totals	# of Points	$RMSE_z$ NVA Spec=0.10 m	NVA –Non-vegetated Vertical Accuracy ($RMSE_z$ x 1.9600) Spec=0.196 m	Mean (m)	Median (m)	Skew	Std Dev (m)	Min (m)	Max (m)	Kurtosis
Non-Vegetated Terrain	26	0.068	0.134	0.046	0.048	-0.454	0.051	-0.081	0.135	0.184

Table 12 - NVA at 95% Confidence Level for Raw Swaths

Inter-Swath (Between Swath) Relative Accuracy

Dewberry verified inter-swath or between swath relative accuracy of the dataset by creating Delta-Z (DZ) orthos. According to the SOW, USGS Lidar Base Specifications v1.2, and ASPRS Positional Accuracy Standards for Digital Geospatial Data, 10 cm Vertical Accuracy Class or QL1 data 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 single or only returns from all classes. 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 areas in the dataset where overlapping flight lines have elevation differences in each pixel greater than 16 cm are colored red. Pixels that do not contain points from overlapping flight lines are colored according to their intensity values. 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, Dewberry may also create

DZ Orthos from the initial ground classification only, while keeping all other parameters consistent. This allows Dewberry 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 usability 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 PR USVI 2018 Lidar are shown in the figure below; this project meets inter-swath relative accuracy specifications.

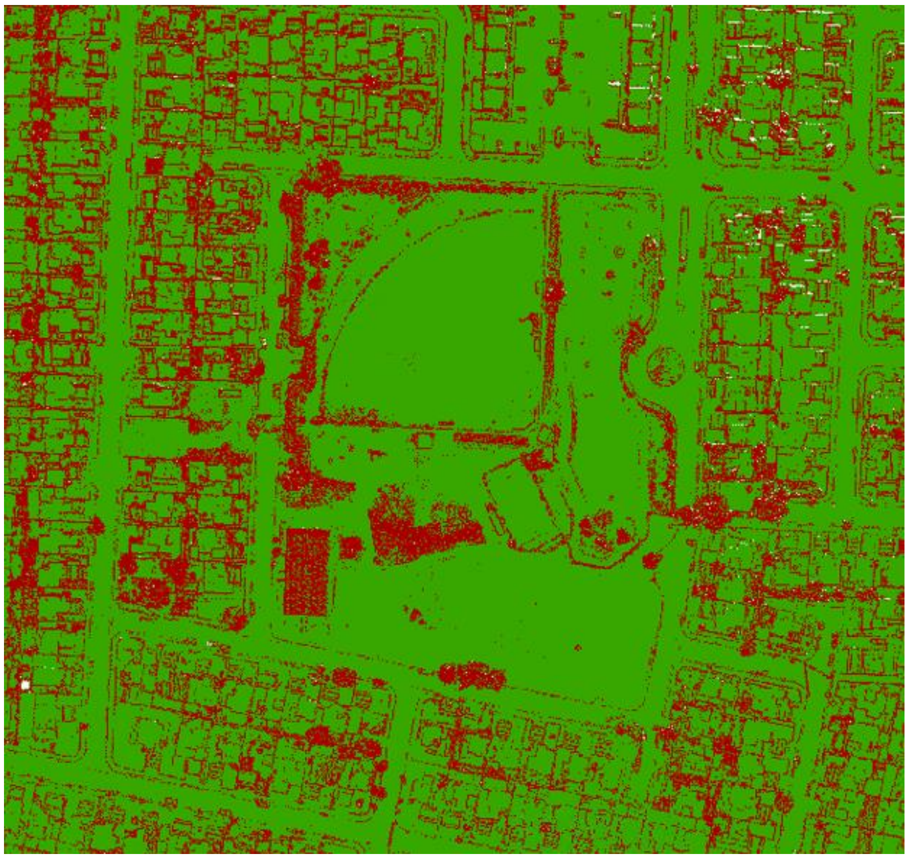


Figure 7 – Single return DZ Orthos for Block B of the PR USVI 2018 Lidar Project. Inter-swath relative accuracy passes specifications.

In addition to the visual qualitative review of interswath values, the Lidar Base Specification 1.3 also outlines specific testing procedures and deliverables to verify that this data is within specification. The specification requires that non-vegetated areas of overlap with slopes less than 10 degrees are tested and reported in a polygon shapefile. This polygon deliverable should contain the minimum, maximum, and RMSDz of the differences in each sample polygon area.

Dewberry has developed a relatively robust process for generating these interswath polygons across the entire dataset. The current specification does not explicitly state the amount of areas to be tested. Dewberry therefore ensures that the assessment is as detailed as possible by creating test polygons for all overlap areas. The test areas are generated such that they are on slopes less than 10 degrees and not in vegetated areas. The generated polygons are then attributed with the min/max/RMSDz statistics. Polygons that intersect large waterbodies are removed from the final results, as these are not reliable test locations.

The result of the process is a shapefile of test polygons with their test values, distributed in all of the overlapping areas across the project area. These polygons are then reviewed for any systematic interswath errors that should be considered of concern.

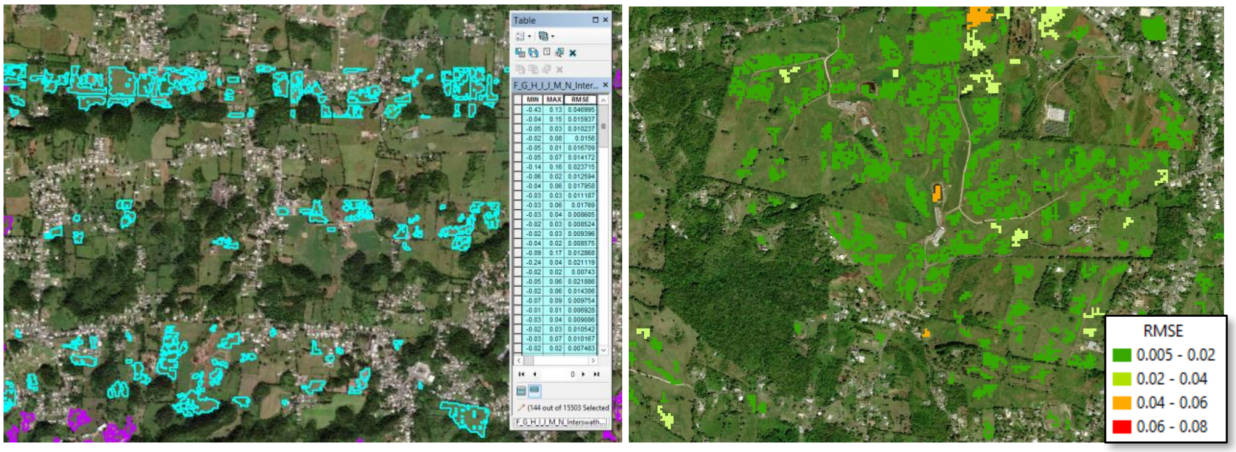


Figure 8 – Left: Interswath polygons and example statistics. Right: Interswath polygons colored by RMSDz values

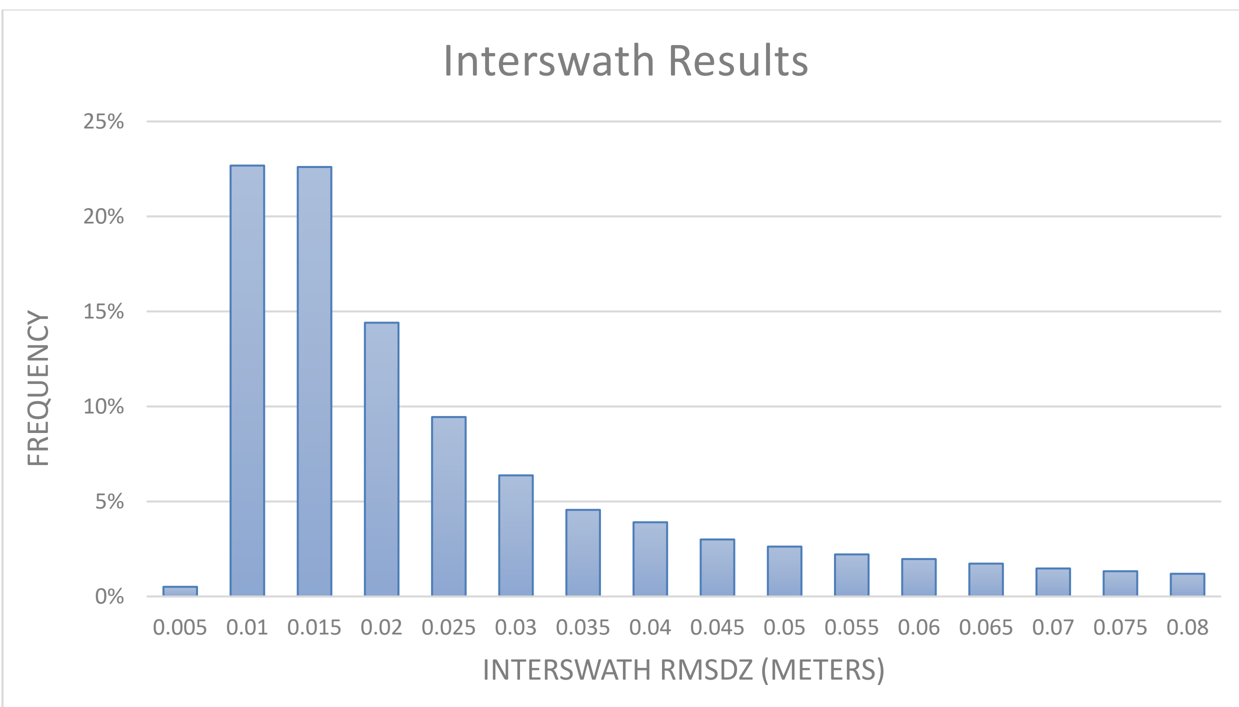


Figure 9 –Frequency distribution of interswath RMSDz results

Intra-Swath (within a Single Swath) Relative Accuracy

Dewberry verifies the intra-swath or within swath relative accuracy by using Quick Terrain Modeler (QTM) scripting and visual reviews. QTM scripting is used to calculate the maximum difference of all points within each 1-meter pixel/cell size of each swath. Dewberry analysts then identify planar surfaces acceptable for repeatability testing and analysts review the QTM results in those areas. According to the SOW, USGS Lidar Base Specifications v1.4 and ASPRS Positional Accuracy Standards for Digital Geospatial Data, 10 cm Vertical Accuracy Class or QL1 data must meet intra-swath relative accuracy of 6 cm maximum difference or less. The image below shows two examples of the intra-swath relative accuracy of the PR-USVI 2018 lidar project; this project meets intra-swath relative accuracy specifications.

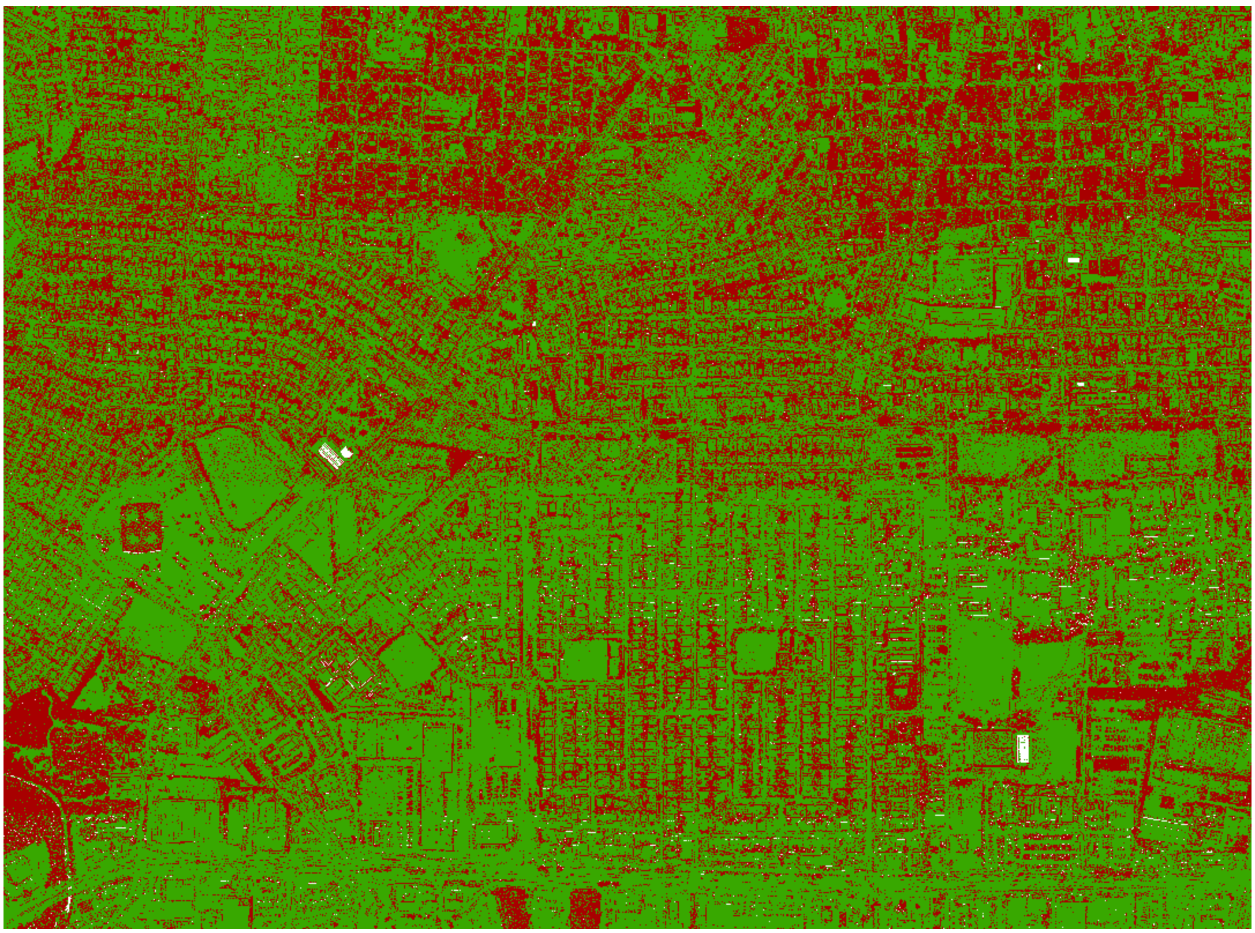


Figure 10 –Intra-swath relative accuracy. The image shows a close-up of Block E1; areas where the maximum difference is ≤6 cm per pixel within each swath are colored green and areas exceeding 6 cm are colored red. Flat, open areas are colored green as they are within 6 cm whereas sloped terrain is colored red because it exceeds 6 cm maximum difference, as expected, due to actual slope/terrain change. With the exception of few trees (shown in red 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.

In addition to the visual qualitative review of intraswath values, the Lidar Base Specification 1.4 also outlines specific testing procedures and deliverables to verify that this data is within specification. The specification requires that test polygons should be drawn in hard surface areas and precision statistical values be computed. The specification calls for each lift to have three (3) test locations. Due to the complexities of this lidar acquisition the resultant dataset has approximately 196 aircraft lifts. Many of these lifts are only a handful of lines and/or reflies. Due to the high number of aircraft lifts, rugged terrain and vegetation through much of the territory, after discussions with USGS Dewberry modified the approach to intraswath testing for this project. Dewberry set one hundred fifty (150) intraswath polygons distributed across the project area where 1/3 of the polygons are located at swath nadir and 2/3 of polygons towards the swath edges. The intraswath polygon deliverable illustrated in Figure 12 contains the minimum, maximum, and RMSDz of the differences in the sample polygon area.

Figure 11 - Intraswath polygons used to test intraswath vertical accuracy.

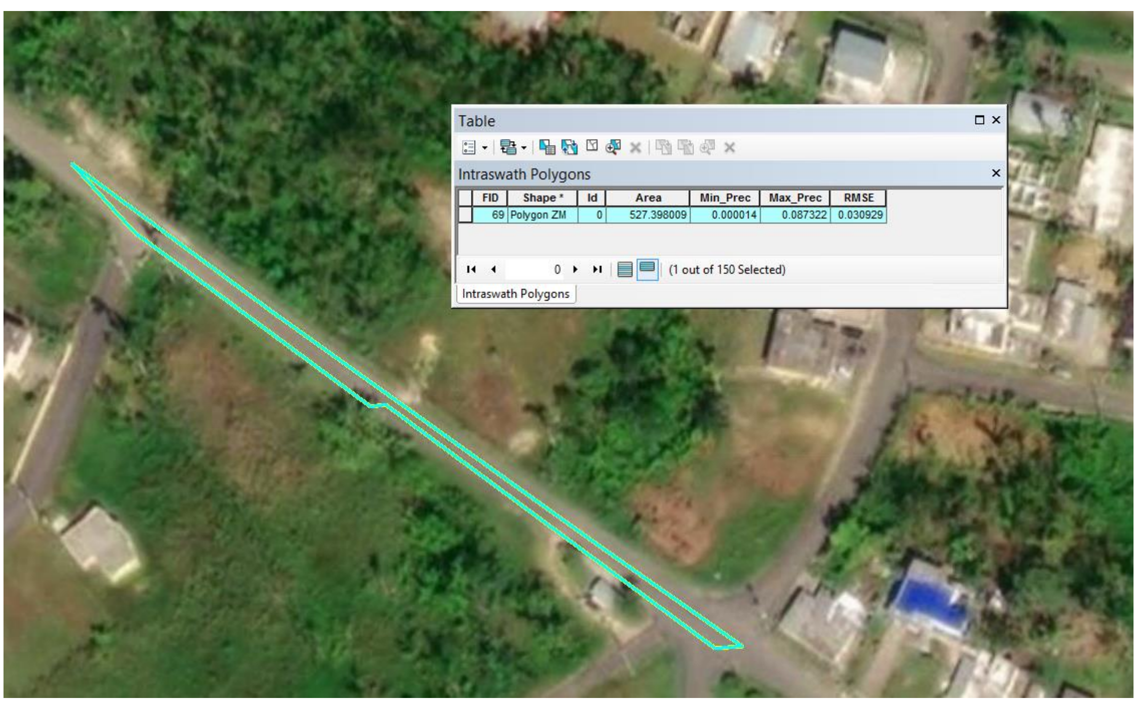


Figure 12 – Example test polygon for intraswath testing, and its results

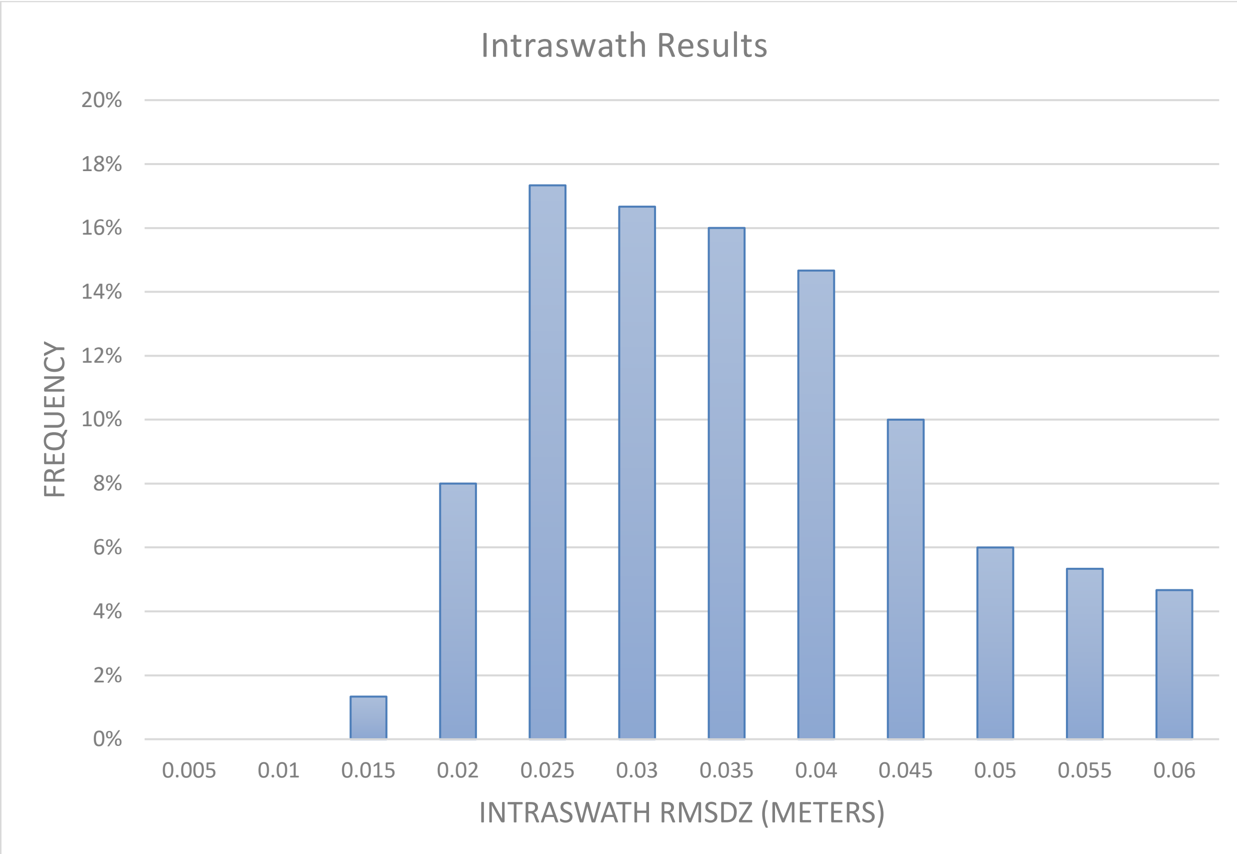


Figure 13 – Frequency distribution of intraswath RMSDz results

Horizontal Alignment

To ensure horizontal alignment between adjacent or overlapping flight lines, Dewberry uses QTM scripting and visual reviews. QTM scripting is used to create files similar to DZ orthos for each swath but this process highlights planar surfaces, such as roof tops. In particular, 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. The image below shows an example of the horizontal alignment between swaths for PR USVI 2018 Lidar project; no horizontal alignment issues were identified.

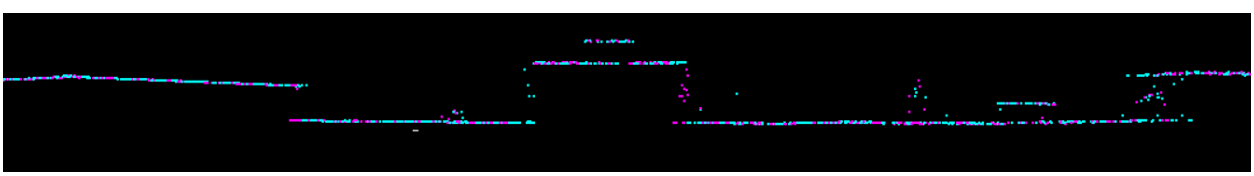


Figure 14 – Horizontal Alignment. Two separate flight lines differentiated by color (Teal/Purple) are shown in this profile. There is no visible offset between these two flight lines. No horizontal alignment issues were identified.

Point Density and Spatial Distribution

The required Aggregate Nominal Point Spacing (ANPS) for this project is no greater than 0.35 meters, which equates to an Aggregate Nominal Point Density (ANPD) of 8 points per square meter or greater. Density calculations were performed using first return data only located in the geometrically usable center portion (typically ~90%) of each swath. By utilizing statistics, the project area was determined to have an NPS of 0.31 meters or an NPD of 10.3 points per square meter which satisfies the project requirements. A visual review of a 1-square meter density grid (figure below) shows that there are some 1-meter cells that do not contain 8 points per square meter (red areas) due to the irregular spacing of lidar point cloud data. Most 1-sqaure meter cells contain at least 8 points per square meter (green areas) and when density is viewed/analyzed by representative 1-square kilometer areas (to account for the irregular spacing of lidar point clouds), density passes with no issues.

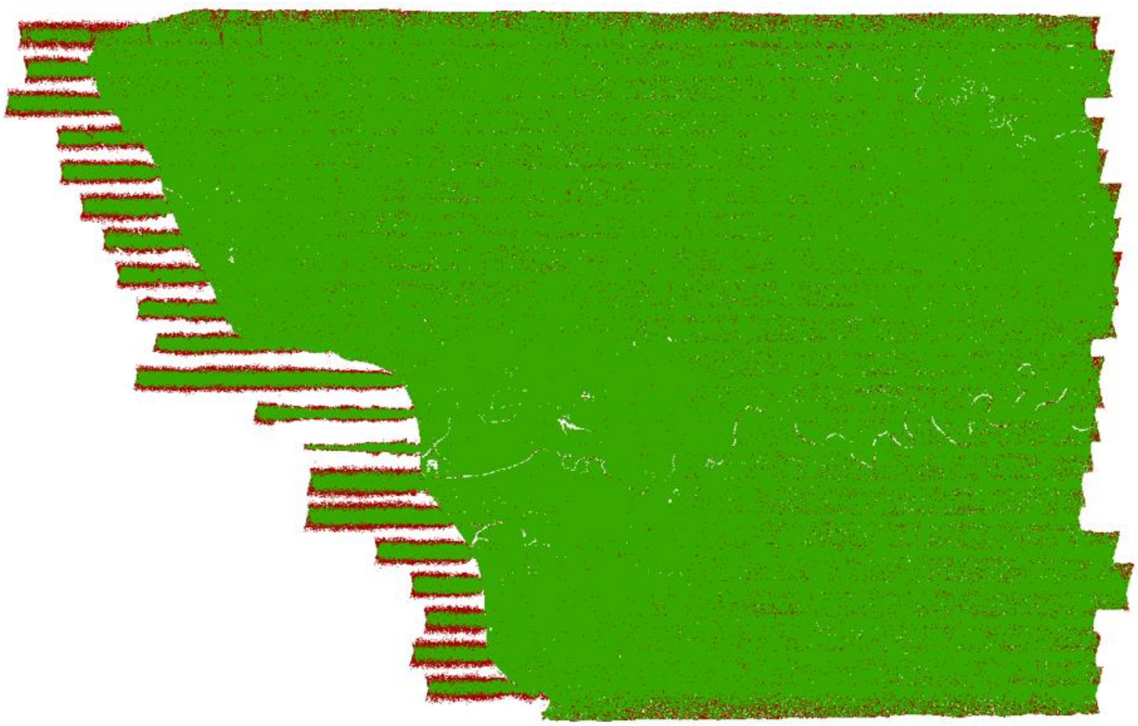


Figure 15 – 1-square meter density grid of Block M. There are some 1-meter cells that do not contain 2 points per square meter (red areas) due to the irregular spacing of lidar point cloud data. Most 1-sqaure meter cells contain at least 8 points per square meter (green areas) showing there are no systematic density issues. When density is viewed/analyzed by representative 1-square kilometer areas, density passes with no issues.

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. ArcGIS tools are 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. This project passes spatial distribution requirements, as shown in the image below.

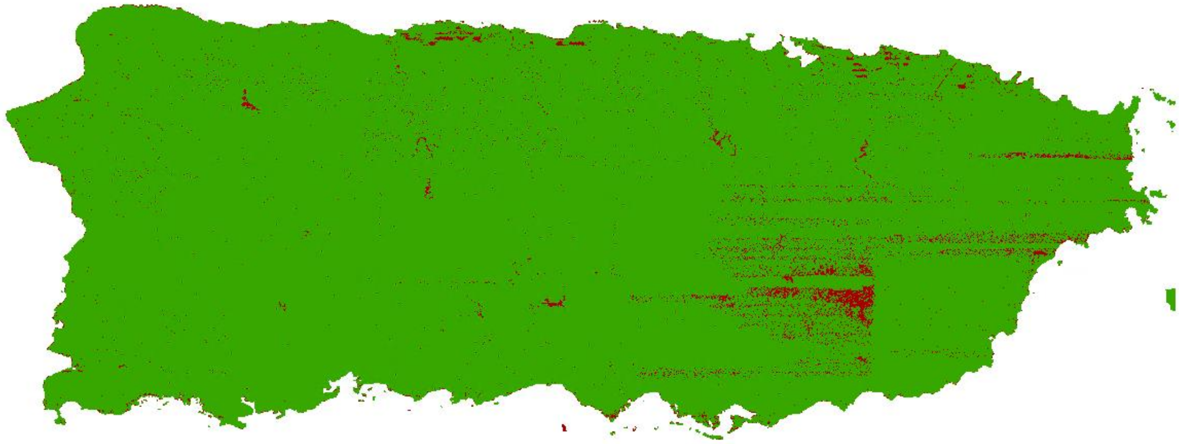


Figure 16 – Spatial Distribution. All cells (2*NPS cellsize) containing at least one lidar point are colored green. Cells that do not contain a lidar point, including water bodies which are acceptable NoData area, are colored red. Without removing acceptable NoData areas due to water, 97.7% of cells contain at least one lidar point.

DATA CLASSIFICATION AND EDITING

Once the calibration, absolute swath vertical accuracy, and relative accuracy of the data was confirmed, Dewberry utilized a variety of software suites for data processing. The data was processed using GeoCue and TerraScan software. The initial step is the setup of the GeoCue 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 GeoCue 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. Dewberry analysts visually reviewed the ground surface model and corrected errors in the ground classification such as vegetation, buildings, and bridges that were present following the initial processing conducted by Dewberry. Dewberry 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. Bridge decks are classified to class 17 using bridge breaklines compiled by Dewberry. After the ground classification corrections were completed, the dataset was processed through a water classification routine that utilizes breaklines compiled by Dewberry 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 1x NPS or less of the hydrographic features are moved to class 20, an ignored ground due to breakline proximity. Overage points are then identified in Terrascan and GeoCue is used to set the overlap bit for the overage points and the withheld bit is set on the withheld points previously identified in Terrascan before the ground 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, or 20, 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

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 GeoCue software and then verified using proprietary Dewberry tools.

Lidar Qualitative Assessment

Dewberry'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.

VISUAL REVIEW

The following sections describe common types of issues identified in lidar data and the results of the visual review for PR USVI 2018 Lidar project.

Data Voids

The LAS files are used to produce density grids using the commercial software package QT Modeler (QTM) which creates a 3-dimensional data model derived from Class 2 (ground) points in the LAS files. Grid spacing is based on the project density deliverable requirement for un-obscured areas. Acceptable voids (areas with no lidar returns in the LAS files) that are present in the majority of lidar projects include voids caused by bodies of water. No unacceptable voids are present in the PR USVI 2018 Lidar project.

Artifacts

Artifacts are caused by the misclassification of ground points and usually represent vegetation and/or man-made structures. The artifacts identified are usually low lying structures, such as porches or low vegetation used as landscaping in neighborhoods and other developed areas. These low lying features are extremely difficult for the automated algorithms to detect as non-ground and must be removed manually. The vast majority of these features have been removed but a small number of these features are still in the ground classification. The limited numbers of features remaining in the ground are usually 0.3 meters or less above the actual ground surface, and should not negatively impact the usability of the dataset.

Figure 17 – Tile number 19QHA39006750. Profile with points colored by class (class 1=yellow, class 2=pink) is shown in the top view and a TIN of the surface is shown in the bottom view. The arrow identifies low vegetation points. A limited number of these small features are still classified as ground but do not impact the usability of the dataset.

Bridge Removal Artifacts

The DEM surface models are created from TINs or Terrains. TIN and Terrain models create continuous surfaces from the inputs. Because a continuous surface is being created, the TIN or Terrain will use interpolation to continue the surface beneath the bridge where no lidar data was acquired. Locations where bridges were removed will generally contain less detail in the bare-earth surface because these areas are interpolated.

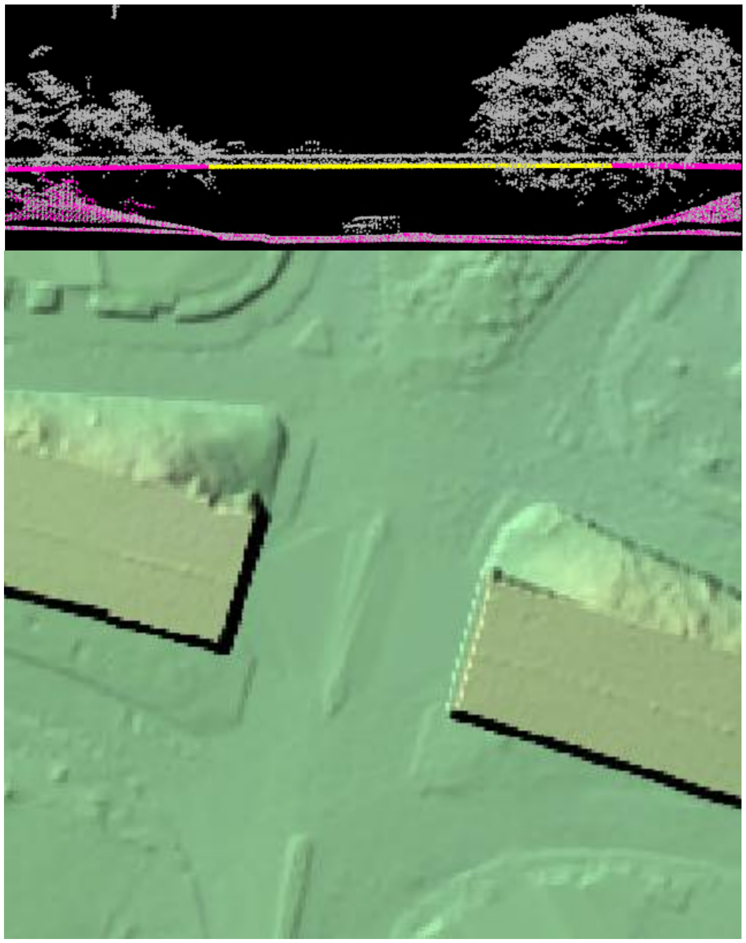


Figure 18 – Tile number 19QHA37506750. The DEM in the bottom view shows an area where a bridge has been removed from ground. The surface model must make a continuous model and in order to do so, points are connected through interpolation. This results in less detail where the surface must be interpolated. The profile in the top view shows the lidar points of this particular feature colored by class. All bridge points have been removed from ground (pink) and are bridge decks (yellow).

Culverts and Bridges

Bridges have been removed from the bare earth surface while culverts remain in the bare earth surface. In instances where it is difficult to determine if the feature is a culvert or bridge, such as with some small bridges, Dewberry erred on assuming they would be culverts especially if they are on secondary or tertiary roads. Below is an example of a culvert that has been left in the ground surface.

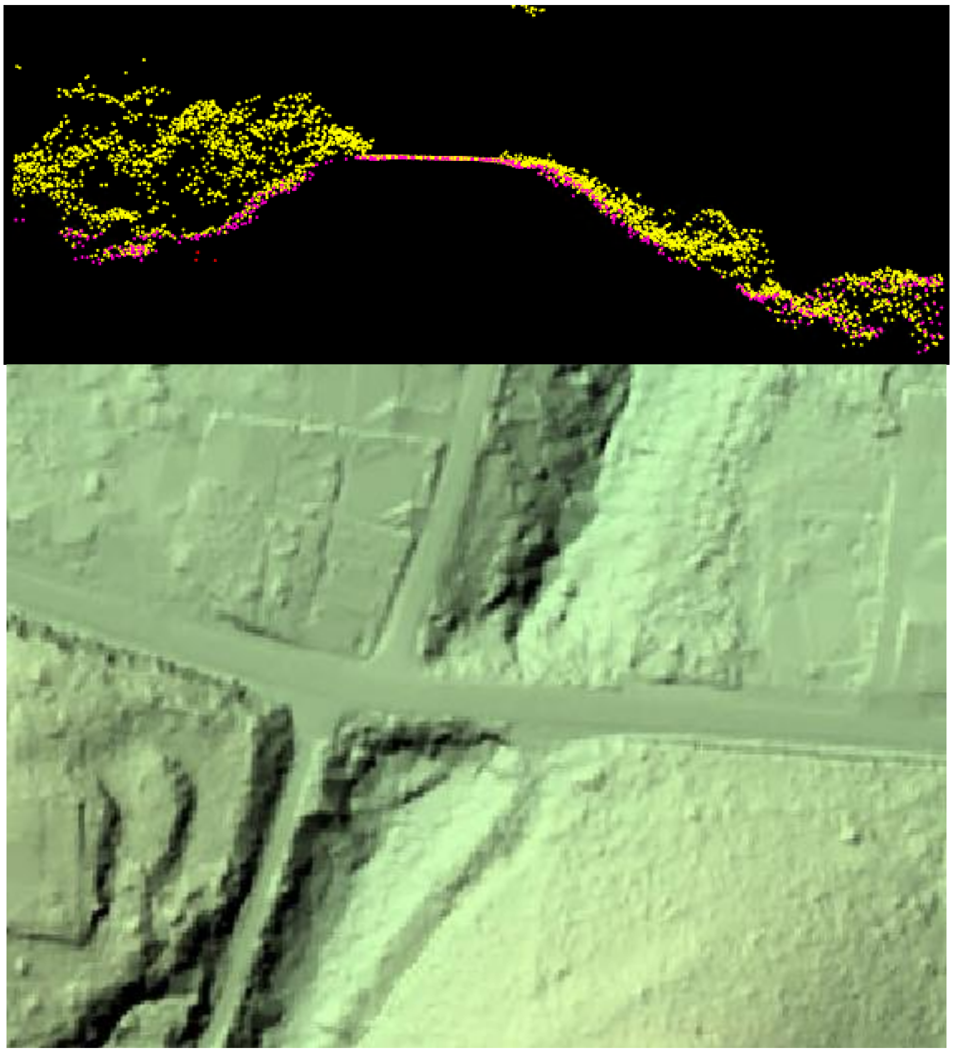


Figure 19 – Tile number 19QGA46007200. Profile with points colored by class (class 1=yellow, class 2=pink) is shown in the top view and the DEM is shown in the bottom view. This culvert remains in the bare earth surface. Bridges have been removed from the bare earth surface and classified to class 17.

Elevation Change within Breaklines

While water bodies are flattened in the final DEMs, other features such as linear hydrographic features can have significant changes in elevation within a small distance. In linear hydrographic features, this is often due to the presence of a structure that affects flow such as a dam or spillway. Dewberry has reviewed the DEMs to ensure that changes in elevation are shown from bank to bank. These changes are often shown as steps to reduce the presence of artifacts while ensuring consistent downhill flow. An example is shown below.

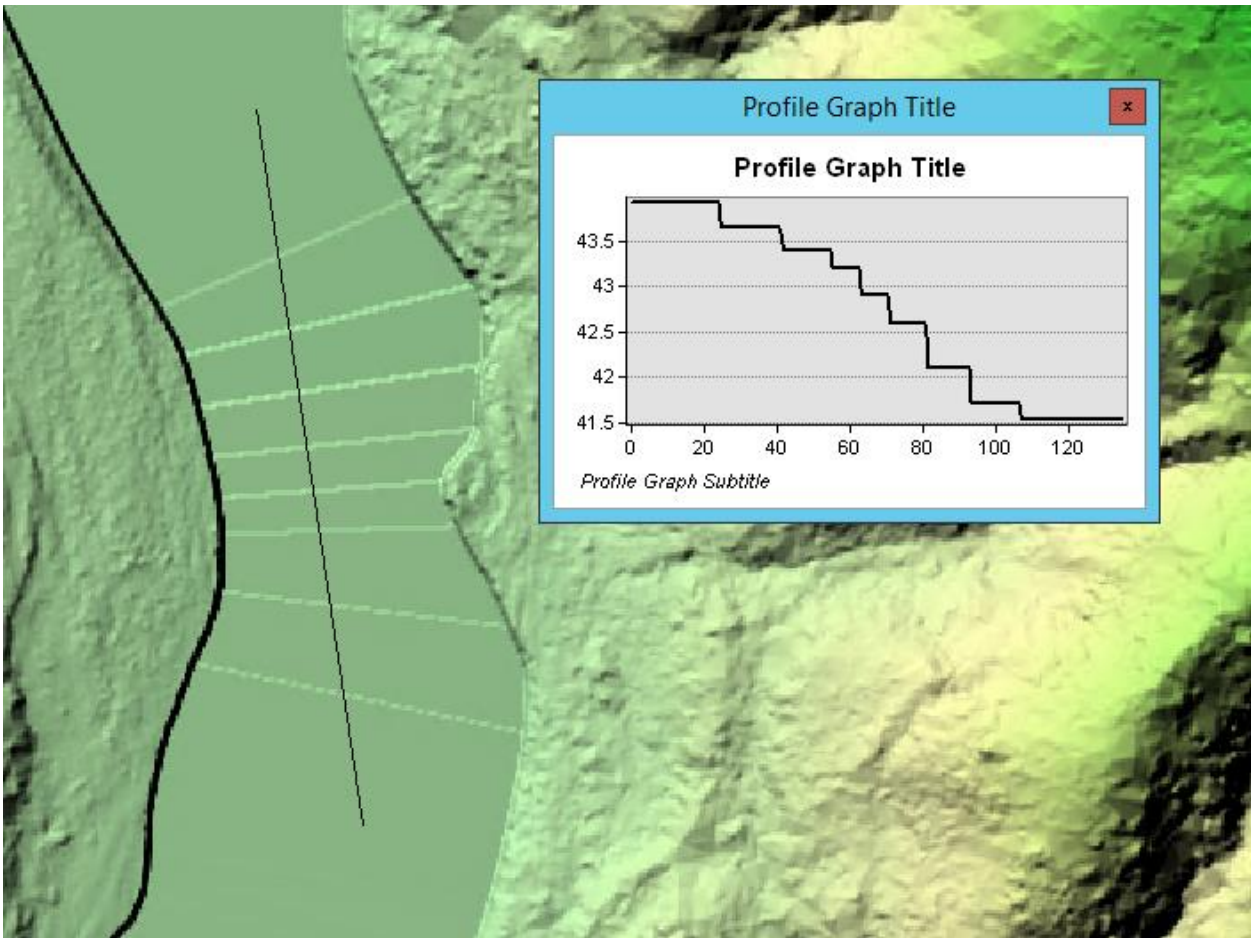


Figure 20 – Tile number 19QGA97005250. Elevation change has been stair stepped. The steps are flat from bank to bank and flow consistently downhill.

Temporal Changes

Because the PR USVI 2018 Lidar project was collected during an ongoing acquisition window between April 2018 and April 2019, there are some temporal differences between the areas collected at different times. The majority of temporal differences are found along water or hydrographic features, but some changes were noted on terrestrial features as well. The most common temporal changes was along hydrographic features, most notably the coastal areas, where adjoining flight lines were from different collects and each flight line was flown at a different tide stage. Terrestrial temporal changes include construction and active changes to the landscape that occurred between April 2018 and April 2019, such as building new irrigation canals or new ramps on a highway construction project. An example is provided below.

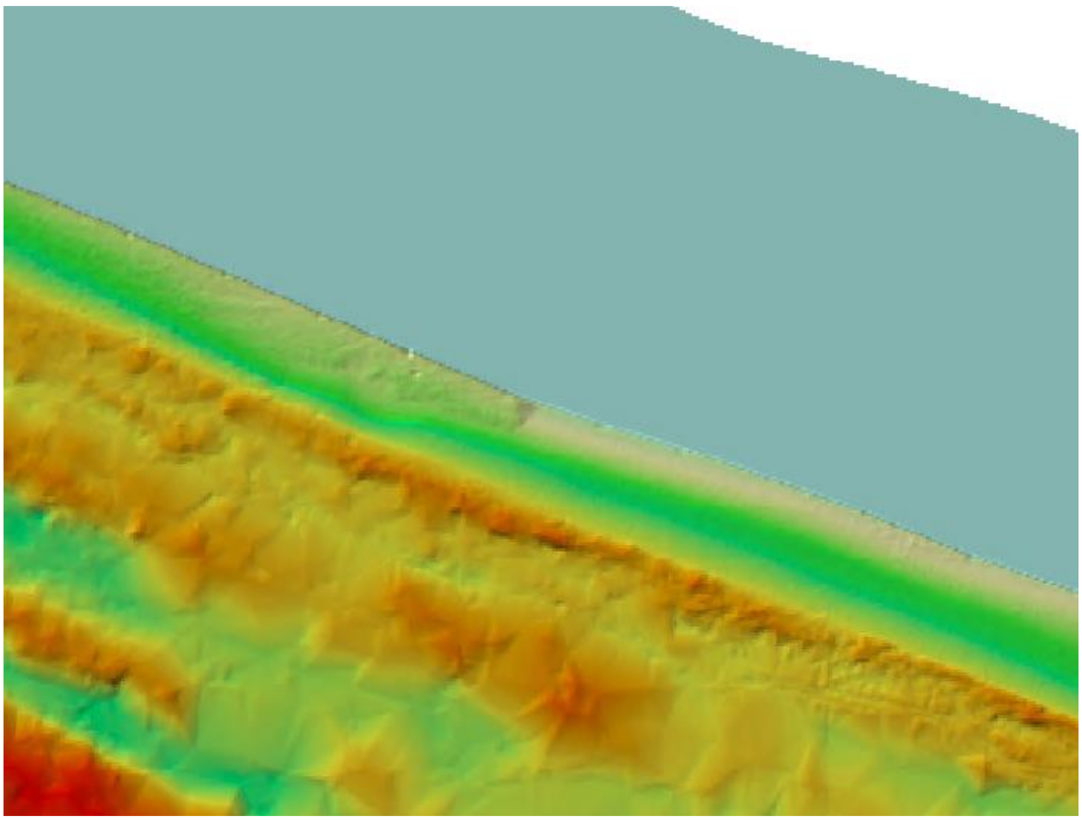


Figure 21 - Tile number 20QJF57006600. This DEM, colored by elevation, shows a temporal change along the coast caused by flightlines from separate missions.

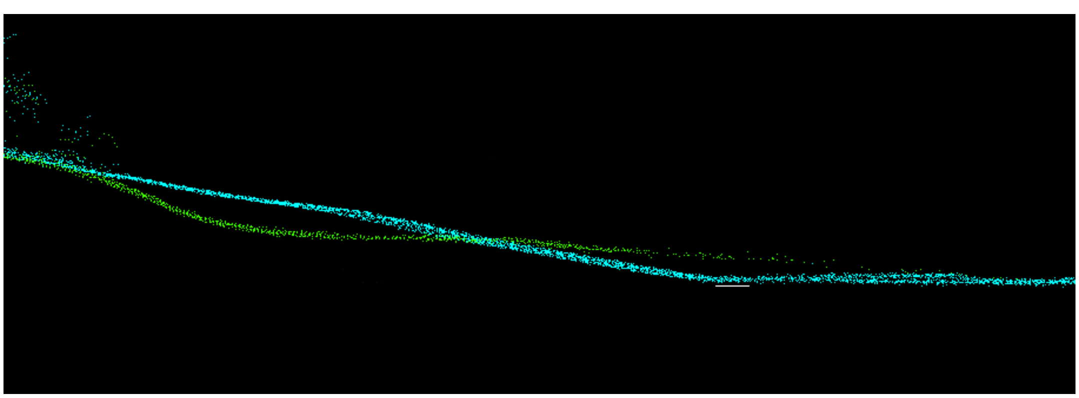


Figure 22 - Tile number 20QJF57006600. Profile showing points colored by flight line.

Ground Voids

Because parts of the PR USVI 2018 Lidar project were collected in areas where there are clouds virtually every day of the year, there are some ground voids. With the current available technology, lidar sensors cannot penetrate clouds. The noise from clouds was removed from the classified lidar dataset, however, this resulted in some areas having ground voids. A shapefile outlining these voids was delivered and an example is provided below.

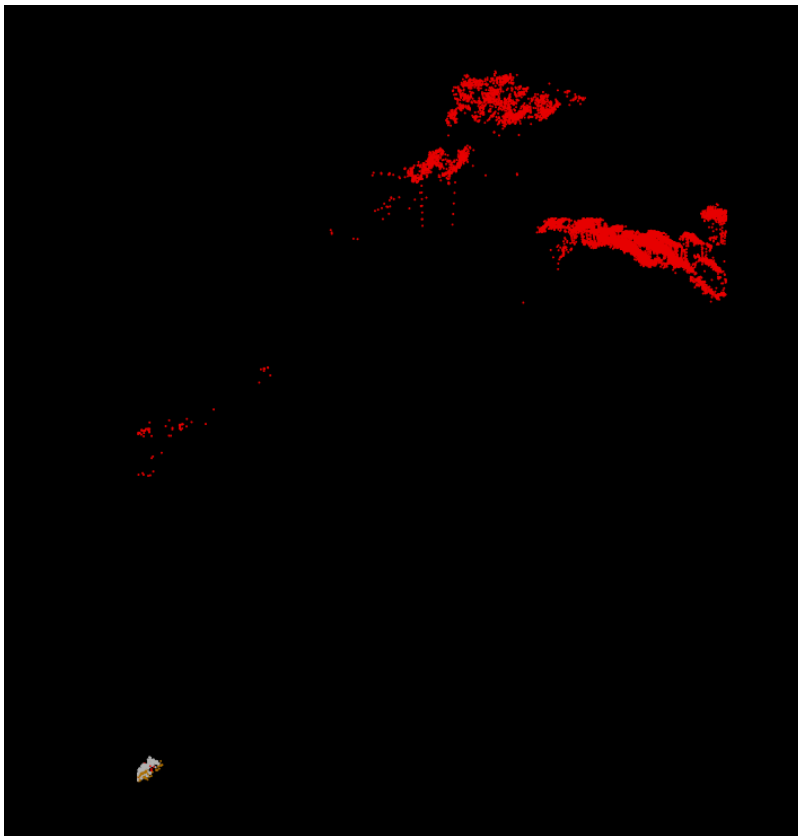


Figure 23 - Tile number 19QHA39003000. Clouds have been removed from the ground class and moved to high noise resulting in a ground void. (Class 1 Unclassified – White, Class 2 Ground – Orange, Class 17 High Noise – Red)

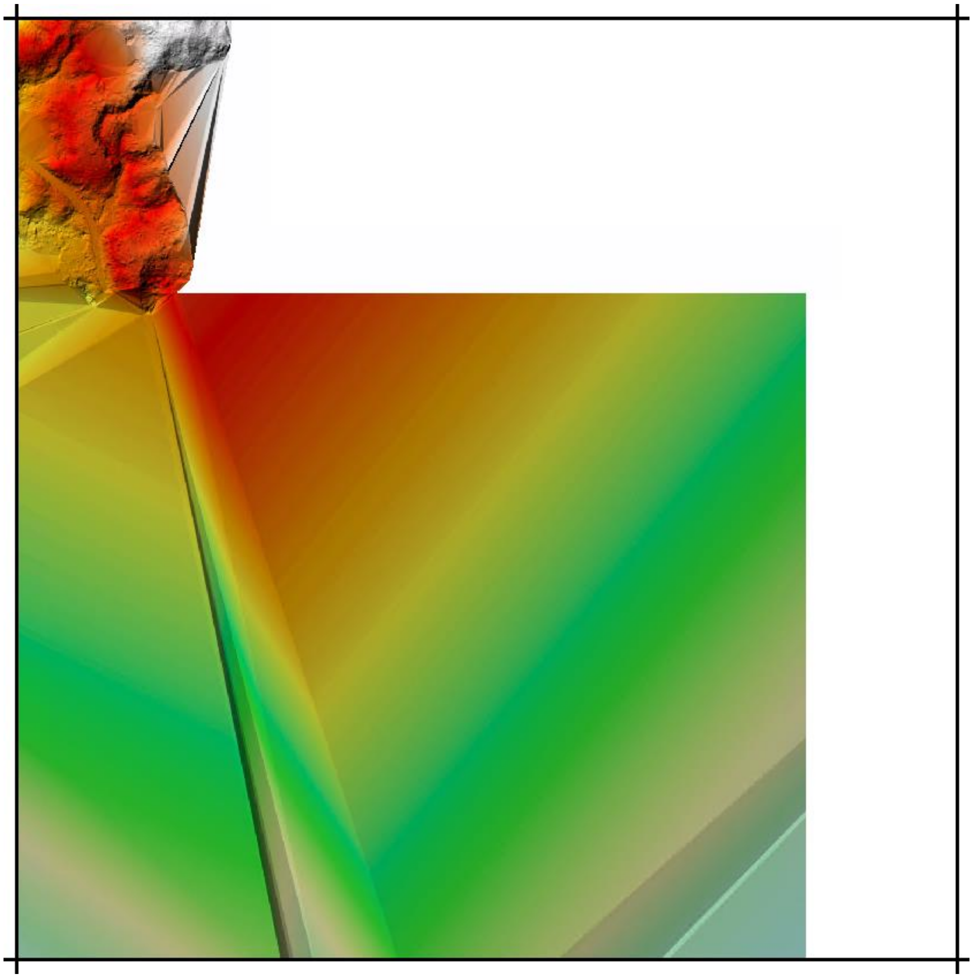


Figure 24 - Tile number 19QHA39003000. DEM overview of an area where clouds were removed causing a ground void.

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. The final formatting, header information, point data records, and variable length records are verified using Dewberry proprietary tools. The table below 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) UTM Zone 18N, meters and PRVD02 or VIVD09 (Geoid 12B), 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 NIIRS10 for GeoCue software	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	Pass
Overlap and Withheld Points	Overlap (Overage) and Withheld points are set to the Overlap and 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 13 – Lidar formatting information

Derivative Lidar Products

USGS required several derivative lidar products to be created. Each type of derived product is described below.

LOW CONFIDENCE POLYGONS

Low confidence polygons have been delivered with this dataset. These polygons represent areas where heavy vegetation greatly diminishes penetration of the lidar pulse, resulting in a bare earth surface that is potentially less accurate due to the lack of lidar returns from the ground beneath the vegetation. Low confidence polygons delineate areas where conformance to VVA standards may not be met. The low confidence polygons created for this dataset were delineated according to the criteria and assumptions outlined in the ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014). Low confidence areas are identified using a ground density raster. All areas with a Nominal Ground Point Density less than a specified threshold are identified as low confidence cells in the ground density raster. The low confidence cells are exported to polygons and aggregated into larger shapes. Areas of expected low density in the ground, such as water or where buildings/structures have been removed, are deleted from the aggregated low confidence polygons. The size of all polygons are then calculated and polygons below the minimum size threshold are removed from the final low confidence polygon dataset.

Lidar Positional Accuracy

BACKGROUND

Dewberry 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 end 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. Dewberry typically uses LP360 software to test the swath lidar vertical accuracy, Terrascan software to test the classified lidar vertical accuracy, and Esri ArcMap to test the DEM vertical accuracy so that three different software programs are used to validate the vertical accuracy for each project.

Dewberry also tests the horizontal accuracy of lidar datasets when checkpoints are photo-identifiable in the intensity imagery. Photo-identifiable checkpoints in intensity imagery typically include checkpoints located at the ends of paint stripes on concrete or asphalt surfaces or checkpoints located at 90 degree corners of different reflectivity, e.g. a sidewalk corner adjoining a grass surface. The XY coordinates of checkpoints, as defined in the intensity imagery, are compared to surveyed XY coordinates for each photo-identifiable checkpoint. These differences are used to compute the tested horizontal accuracy of the lidar. As not all projects contain photo-identifiable checkpoints, the horizontal accuracy of the lidar cannot always be tested.

SURVEY VERTICAL ACCURACY CHECKPOINTS

For the vertical accuracy assessment, two hundred and thirty-two (232) check points were surveyed for the project and are located within bare earth/open terrain, grass/weeds/crops, and forested/fully grown land cover categories. Please see appendix A to view the survey report which details and validates how the survey was completed for this project.

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

All checkpoints surveyed for vertical accuracy testing purposes are listed in the following table.

Point ID	NAD83 (2011) UTM Zone 18N		NAVD88 (Geoid 12B)
	Easting X (m)	Northing Y (m)	Elevation (m)
NVA-001	118857.83	216521.47	12.06

NVA-002	134951.85	215643.56	0.74
NVA-003	143719.43	215315.59	30.42
NVA-004	154289.93	222178.58	58.37
NVA-005	164551.37	219305.33	1.58
NVA-006	167707.58	231317.58	896.44
NVA-007	141709.24	230087.65	208.02
NVA-008	135309.31	229620.52	40.96
NVA-009	129543.83	232761.18	31.66
NVA-010	120082.28	227867.51	11.42
NVA-011	125438.65	240155.07	11.89
NVA-012	135386.52	240058.23	354.18
NVA-013	142816.98	234095.68	831.05
NVA-014	156350.09	239950.26	602.12
NVA-015	168904.61	237364.5	485.48
NVA-016	123560.13	252136.87	28.31
NVA-017	137606.29	247012.55	373.76
NVA-018	155164.94	247719.87	517.48
NVA-019	160985.47	250566.28	399.42
NVA-020	170081.49	248489.37	166.72
NVA-021	160469.37	257370.43	341.01
NVA-022	148136.25	262471.77	199.84
NVA-023	134591.59	259403.72	75.37
NVA-024	113653.9	255612.41	4.48
NVA-025	124468.96	272189.04	75.83
NVA-026	143571.24	266558.19	186.12
NVA-027	136469.87	269293.75	146.55
NVA-028	151002.92	269568.29	103.7
NVA-029	161893.68	265763.2	135.38
NVA-030	169951.6	270821.28	10.58
NVA-031	184700.6	272010.37	3.35
NVA-032	188399.43	267132.41	9.66
NVA-033	200976.29	267208.26	30.41
NVA-034	209284.85	269470.01	9.27
NVA-035	219073.65	264090	9.56
NVA-036	220515.54	251571.67	100.34
NVA-037	205981.99	255576.11	149.18
NVA-038	195579.71	258675.53	99.71

NVA-039	185209.89	257533.55	187.3
NVA-040	174137.03	255349.98	324.14
NVA-041	171661.78	248010.04	137.08
NVA-042	182171.03	246325.92	660.28
NVA-043	204075.87	248743.91	610.03
NVA-044	212863.19	245659.79	538.11
NVA-045	222240	242941.1	207
NVA-046	221555.15	239036.34	506.61
NVA-047	212054.57	239514.43	629.75
NVA-048	191970.92	236242.4	805.56
NVA-049	180951.3	236031.58	874.29
NVA-050	175453.27	233348.19	579.71
NVA-051	171872.52	225272.6	87.52
NVA-052	179526.73	225345.53	190.64
NVA-053	192873.9	227103.5	74.03
NVA-054	204835.48	232289.38	577.37
NVA-055	214393.35	227314.62	206.24
NVA-056	219572.59	218613.07	43.58
NVA-057	202205.25	215214.49	10.39
NVA-058	192748.72	218585.22	6.68
NVA-059	181927.41	215262.53	2.4
NVA-060	172695.53	215795.81	5.86
NVA-061	233491.99	215819.93	46.47
NVA-062	242594.41	216789.86	11.33
NVA-063	253550.79	219386.78	19.22
NVA-064	262912.92	222801.74	12.36
NVA-065	255668.17	224924.9	24.37
NVA-066	246788.27	227344.72	336.42
NVA-067	236169.63	224594.54	567.59
NVA-068	227144.54	228782.82	536.8
NVA-069	228295.92	234221.85	369.5
NVA-071	247995.5	234369.16	169.45
NVA-072	256908.52	234754.53	297.75
NVA-073	264780.45	230898.69	27.12
NVA-074	271995.44	236850.81	1.27
NVA-075	262524.51	241432.65	106.18
NVA-076	248115.52	242993.88	99.63

NVA-077	239750.49	244607.93	76.97
NVA-078	230745.75	245175.37	294.16
NVA-079	228465.37	254512.22	80.25
NVA-080	236302.86	253101.14	120.14
NVA-081	247284.58	252812.49	210.01
NVA-082	257208.51	253168.41	109.56
NVA-084	279640.61	243636.34	17.55
NVA-085	281607.87	255864.22	13.64
NVA-086	269831.55	259482.54	13.61
NVA-087	258196.28	265762.18	2.8
NVA-088	247673.43	265942.64	1.88
NVA-089	235799.58	261778.07	31.28
NVA-090	227063.26	267208.53	2.14
NVA-091	298155.57	233424.05	1.87
NVA-092	297991.33	229310.57	27.25
NVA-093	300972.42	229881.63	21.52
NVA-094	305623.58	235582.45	12.33
NVA-095	305384.07	232131.71	29.62
NVA-096	321076.77	250926.85	20.08
NVA-097	319415.15	253281.06	2.89
NVA-098	322386.82	252256.17	3.32
NVA-099	348664.397	258031.497	138.44
NVA-100	351229.5	259066.041	113.301
NVA-101	353651.69	258504.726	272.587
NVA-102	354952.782	256714.489	4.836
NVA-103	356452.702	259753.116	42.861
NVA-104	357504.234	257295.713	137.968
NVA-105	360499.939	259041.566	58.817
NVA-106	360005.52	255980.884	3.167
NVA-107	362749.435	253889.205	3.457
NVA-108	361966.487	256549.538	72.78
NVA-109	363862.162	256759.242	115.506
NVA-110	366521.819	256539.119	6.58
NVA-111	366270.965	254781.086	14.49
NVA-112	373392.227	254942.743	58.607
NVA-113	375162.308	254394.098	43.456
NVA-114	375377.629	256960.918	214.922

NVA-115	378986.197	257665.979	285.442
NVA-116	380524.061	256039.384	327.946
NVA-117	380658.6	258486.864	152.862
NVA-118	383149.054	253979.637	7.437
NVA-119	382639.245	255713.929	11.201
NVA-120	381538.721	257367.686	1.815
NVA-121	378847.738	259701.997	7.559
NVA-122	383124.435	258698.923	2.048
NVA-123	385954.916	257848.575	29.811
NVA-124	366080.502	185170.652	14.342
NVA-125	364371.431	189209.859	7.589
NVA-126	363993.958	192759.223	3.65
NVA-127	367549.689	191693.726	214.013
NVA-128	367324.896	188388.187	221.424
NVA-129	368604.859	186692.314	35.258
NVA-130	371137.137	186410.628	31.144
NVA-131	373448.707	185694.898	3.184
NVA-132	371590.035	189494.043	50.535
NVA-133	371191.91	191469.682	89.76
NVA-134	374797.187	195140.724	5.95
NVA-135	375141.531	189969.163	38.831
NVA-136	376493.359	187865.062	20.335
NVA-137	380477.306	187901.613	31.871
NVA-138	376831.53	192025.502	22.74
NVA-139	379903.334	193176.884	6.093
NVA-140	382345.185	191267.746	13.102
NVA-141	384524.985	188030.185	25.76
NVA-142	387273.422	189609.387	23.385
NVA-143	386093.576	191986.92	1.534
NVA-144	390464.242	191457.621	64.185
NVA-145	393441.892	192333.917	1.947
NVA-146	375650.161	255638.92	234.039
VVA-001	319512.53	254636.77	107.09
VVA-002	323425.2	252634.51	56.63
VVA-003	320714.02	253486.46	1.81
VVA-004	317591.51	255150.39	2.09
VVA-005	320160.98	252243.84	4.91

VVA-006	299345.45	229616.14	26.59
VVA-007	309724.98	231476.17	9.3
VVA-008	304901.25	234079.55	40.09
VVA-009	299690.44	230831.68	77.47
VVA-010	293645.14	231544.79	6.33
VVA-011	283160.06	252768.49	10.14
VVA-012	266865.71	258764.96	30.59
VVA-013	255646.25	261575.46	6.05
VVA-014	241995.83	259543.03	51.7
VVA-015	231063.04	255023.53	46.41
VVA-016	234988.72	248641.16	426.8
VVA-017	247325.75	249119.99	65.19
VVA-018	254391.2	250579.73	154.36
VVA-020	273614.76	244586.13	60.26
VVA-022	264869.69	241189.68	120.73
VVA-023	253347.43	240396.47	227.31
VVA-024	243750.11	238646.06	304.14
VVA-025	233433.92	238200.16	455.68
VVA-026	228659.01	225321.78	311.17
VVA-027	233790.76	218276.68	80.31
VVA-028	242774.834	221836.313	72.613
VVA-029	251502.41	226022.78	250.95
VVA-033	201245.62	237420.19	860.05
VVA-033A	201197.68	237416.25	860.98
VVA-034	183439.76	237259.68	1141.72
VVA-035	173045.13	234825.23	760.31
VVA-036	175212.02	223878.08	63.71
VVA-037	185516.91	219004.74	3.57
VVA-038	196116.06	231851.42	368.09
VVA-039	201536.87	219683.18	38.92
VVA-040	211185.64	229669.18	277.69
VVA-041	222836.75	221738.31	111.43
VVA-042	225829.78	249220.1	413.88
VVA-043	210384.57	246902.06	622.74
VVA-044	194314.27	243523.73	663.71
VVA-045	175906.76	245872.24	271.59
VVA-046	181905.7	254424.91	176.33

VVA-047	176526.41	268236.61	14.45
VVA-048	195801.75	265077.76	79.73
VVA-049	199992.5	255784.71	183.66
VVA-050	206383.75	269596.62	2.99
VVA-051	217826.22	266753.12	6.02
VVA-052	223109.33	258303.2	54.88
VVA-053	168327.78	264723.86	126.31
VVA-054	154816.01	265748.45	161.96
VVA-055	136519.78	267205.29	187.78
VVA-056	130381.01	272512.53	57.83
VVA-057	118775.76	258924.25	67.24
VVA-058	133736.03	253392.77	191.98
VVA-059	143971.9	257033.43	295.09
VVA-060	163729.85	256293.75	299.8
VVA-061	162990.71	248078.01	632.75
VVA-062	145029.42	246539.35	411.67
VVA-063	130402.6	246204.19	268.63
VVA-064	130838.26	239767.99	189.64
VVA-065	147459.76	238544.58	711.38
VVA-066	164020.89	239544.56	547.32
VVA-067	162055.38	232095.91	646.59
VVA-068	144562.55	229397.25	225.6
VVA-069	125885.32	226218.35	145.19
VVA-070	124902.89	218962.35	7.72
VVA-071	136032.91	221483.39	13.94
VVA-072	149265.52	219321.26	9.94
VVA-073	165494.38	220872.15	13.21
VVA-074	351013.683	258460.217	208.113
VVA-075	357197.199	258169.284	395.77
VVA-076	361879.303	256246.998	76.426
VVA-077	374466.025	255874.651	122.396
VVA-078	379907.74	256681.229	340.767
VVA-079	381807.282	257855.684	10.526
VVA-080	363504.32	191132.27	17.8
VVA-081	370239.23	189236.71	76.98
VVA-082	374075.28	188225.6	24.58
VVA-083	376629.68	192784.96	17.26

VVA-084	382339.25	188243.46	35.09
VVA-085	388150.86	190751.72	33.83
VVA-249	285026.065	258972.962	43.821
VVA-621	287256.378	242517.050	4.036

Table 14 - PR USVI 2018 lidar surveyed accuracy checkpoints

Two hundred and thirty-two checkpoints were surveyed for vertical accuracy testing. While reviewing the final coordinates of the provided survey checkpoints against the field sketches and intensity imagery created from the lidar, Dewberry identified issues with the location of some checkpoints. The location of checkpoints as recorded in field sketches did not match the location of the provided checkpoints. For example, a field sketch may have shown that the checkpoint should be located west of a road, but the final coordinates show that the checkpoint's true location is east of a road. Upon discussion and review by the surveyor, it was determined that some checkpoints were given erroneous coordinates and elevations. Points were collected using the conventional method and in some instances, points that were surveyed were reversed during calculations. The two points were re-calculated by the surveyor and the new coordinates were used in the final vertical accuracy testing. Additionally, some checkpoints (from all land cover categories) had large delta Z errors during vertical accuracy testing that could not be attributed to characteristics of the lidar data. These checkpoints were reviewed by the surveyor to check for additional surveying issues. After reviewing and reprocessing the calculations, several checkpoints were modified with revised coordinates and elevations. The revised coordinates and elevations were used in the final vertical accuracy testing. Table 15, above, includes all revised coordinates and contains the final coordinates as used in the vertical accuracy testing. The revised coordinates provided by the surveyor can also be found in Appendix A.

Four checkpoints (NVA-070, NVA-083, VVA-019, and VVA-021) were removed from the vertical accuracy testing for the classified lidar due to being located in lidar voids caused by a lack of swath coverage. Three checkpoints (VVA-030, VVA-031, and VVA-032) were removed from the vertical accuracy testing for the classified lidar due to being located in areas where not enough ground points were available to make a reliable comparison, as checkpoints need to be placed in locations where light can be reached. The coordinates of these checkpoints and example screenshots are provided below.

Point ID	NAD83(2011) State Plane VA		NAVD88 (Geoid 12B)	Lidar Z (ft)	Delta Z	AbsDeltaZ
	Easting X (ft)	Northing Y (ft)	Survey Z (ft)			
NVA-070	238317.580	232978.890	510.090	N/A	N/A	N/A
NVA-083	268481.250	251871.410	642.910	N/A	N/A	N/A
VVA-019	268137.260	251398.750	721.440	N/A	N/A	N/A
VVA-021	280170.570	246720.580	151.770	N/A	N/A	N/A
VVA-030	244286.510	230424.410	541.410	541.850	0.440	0.440
VVA-031	266491.270	226605.790	52.560	53.240	0.680	0.680
VVA-032	221302.060	241874.980	203.930	204.300	0.370	0.370

Table 15 - Checkpoints removed from vertical accuracy testing.

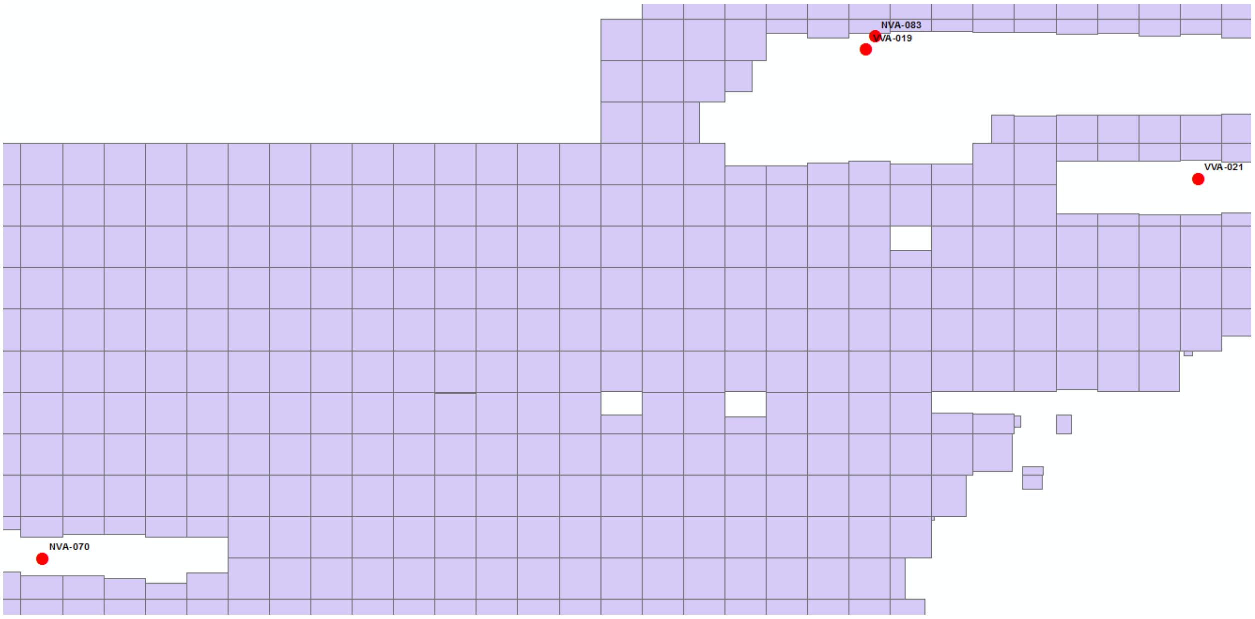


Figure 25 – Checkpoints NVA-070, NVA-083, VVA-019, and VVA-021, shown as the red circles, are located outside of the LAS extents coverage, shown in purple. These checkpoints were removed from all vertical accuracy calculations due to their locations in void areas.

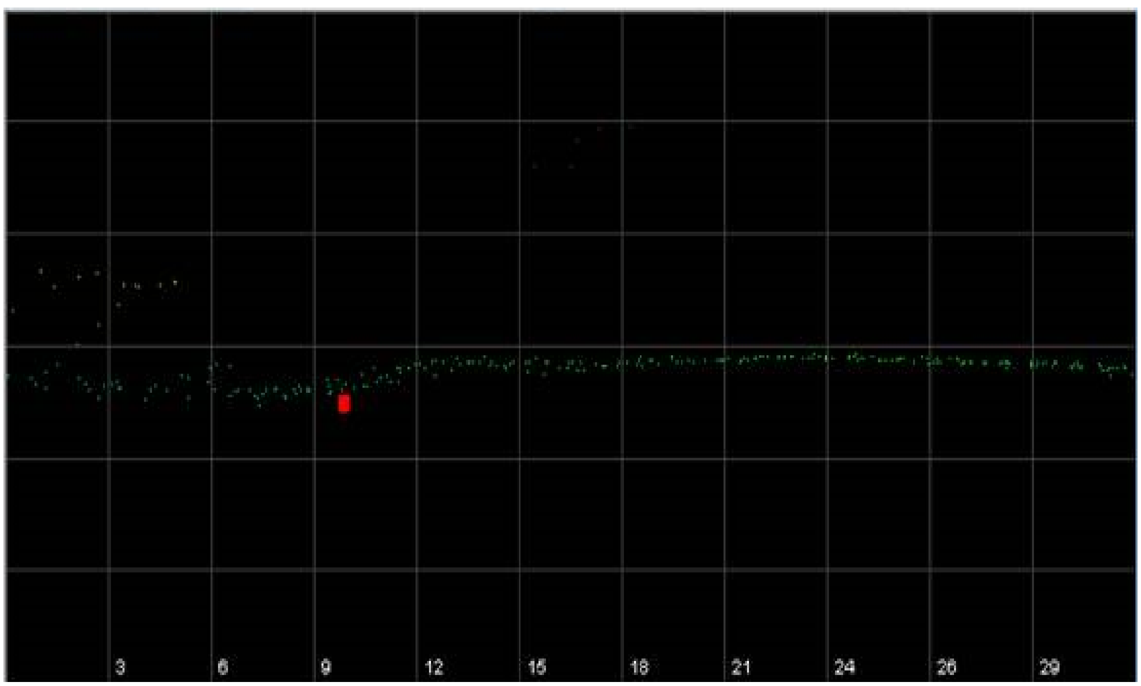


Figure 26 – Checkpoint VVA-030, shown as the red rectangle in the profile, is located in a highly vegetated area. This checkpoint was removed from all vertical accuracy calculations due the lidar's inability to penetrate the dense vegetation.

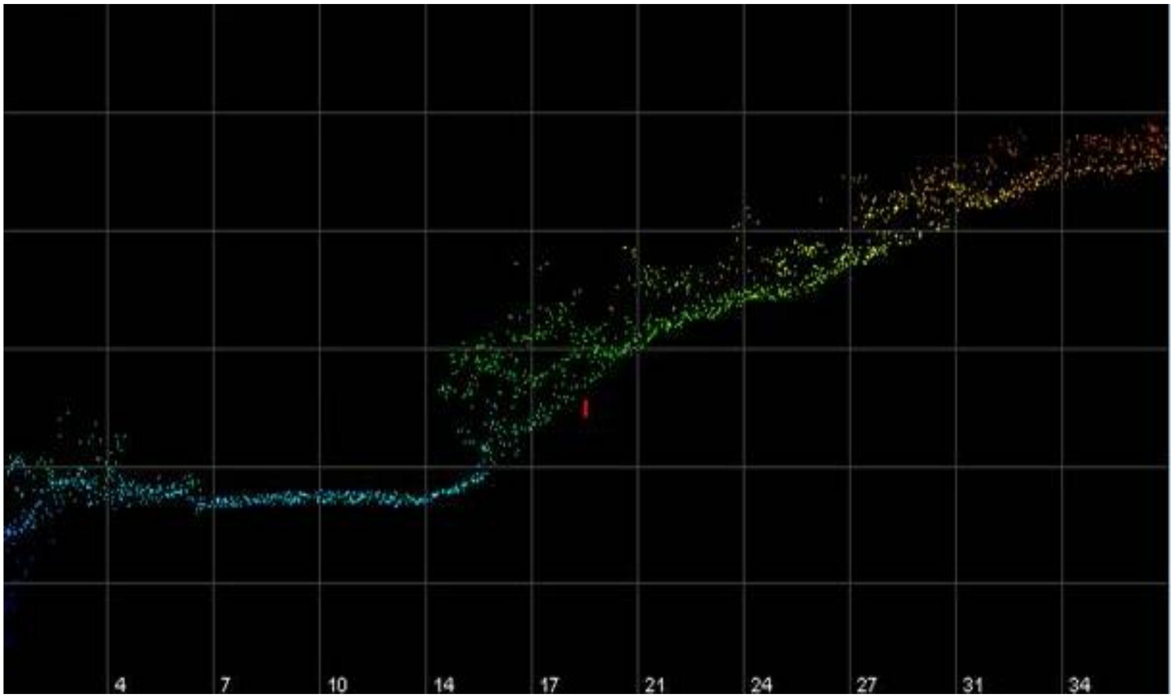


Figure 27 – Checkpoint VVA-031, shown as the red rectangle in the profile, is located in a highly vegetated area. This checkpoint was removed from all vertical accuracy calculations due the lidar's inability to penetrate the dense vegetation.

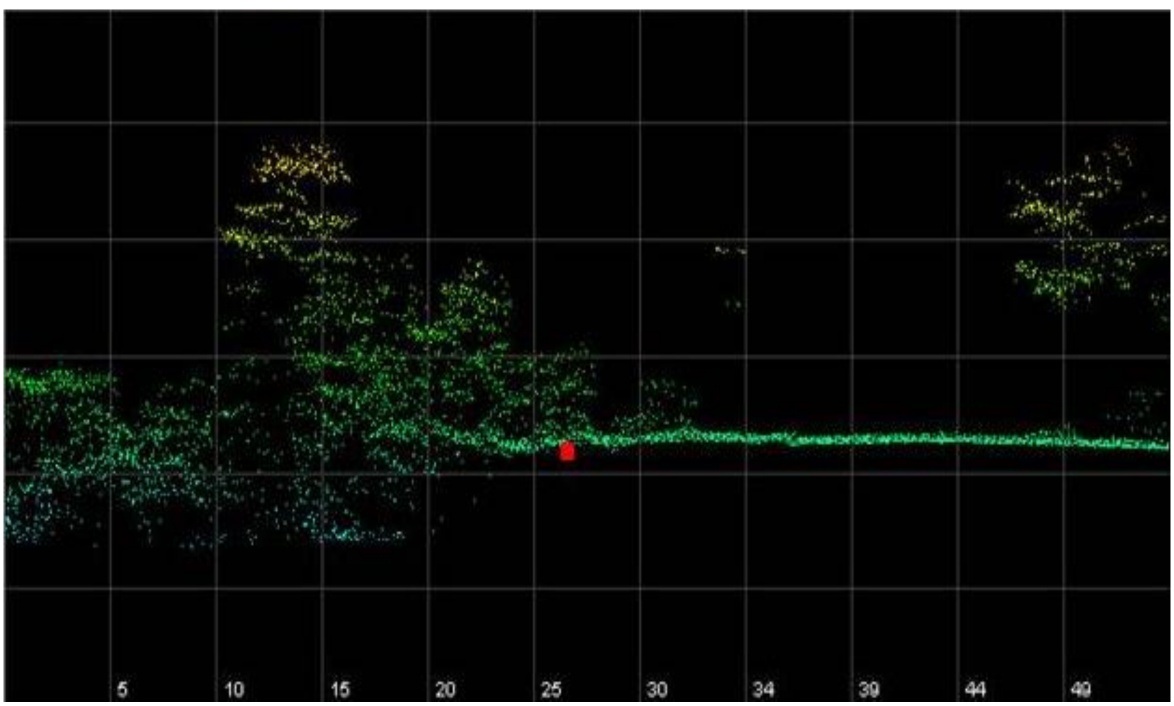


Figure 28 – Checkpoint VVA-032, shown as the red rectangle in the profile, is located in a highly vegetated area. This checkpoint was removed from all vertical accuracy calculations due the lidar's inability to penetrate the dense vegetation.

Due to the number of checkpoints that needed to be removed for the reasons mentioned above, two checkpoints (VVA-249 and VVA-621) were added in order to meet the minimum requirements as specified by the task order. These checkpoints were collected in 2019 as a part of the NOAA Puerto Rico topobathy lidar project and were used for testing the final classified LAS. The coordinates are listed in table format below along with the survey photos.

Point ID	NAD83(2011) State Plane VA		NAVD88 (Geoid 12B)	Lidar Z (ft)	Delta Z	AbsDeltaZ
	Easting X (ft)	Northing Y (ft)	Survey Z (ft)			
VVA-249	285026.065	258972.962	43.821	43.890	0.069	0.069
VVA-621	287256.378	242517.050	4.036	4.060	0.024	0.024

Table 16 - Checkpoints added to vertical accuracy testing.

Dewberry

CHECK POINT DOCUMENTATION REPORT

Date: 3-27-2019 Time: 12:38 ☐ a.m. ☒ p.m. Employee Name: DAVID JAMESON
Job Name: PR/VI Hurricane Maria Imagery and LiDAR CP Point ID: VVA-249
State: PR Latitude: ☐ + ☐ - Longitude: ☐ + ☐ -
Address and/or Intersection:

OBSERVATION METHOD

☒ VRS GPS	RMS: H: V: Duration: 3 MIN
☐ STATIC GPS	(20 min.) Start Time: ☐ a.m. ☐ p.m. End Time: ☐ a.m. ☐ p.m.
☐ Conventional Pairs VRS	Point Number: RMS: H: V: Duration: Point Number: RMS: H: V: Duration:
☐ Conventional Pairs STATIC	(20 min.) Point Number: Start Time: ☐ a.m. ☐ p.m. End Time: ☐ a.m. ☐ p.m. Point Number: Start Time: ☐ a.m. ☐ p.m. End Time: ☐ a.m. ☐ p.m.
☐ Occupied Point	Pt. #/HT: / ☐ BS Pt. #/HT: / ☐ FS Pt. #/HT: /
☐ Back Site Point	Distance: Vertical Angle: ☐ Angle 00°00'00"
☐ FS Point	Angle: Vertical Angle: Slope Distance: Horizontal Distance:

TYPE OF CHECK POINT

☐ NVA: OPEN Terrain
☐ VVA: GWC Terrain
☐ VVA: BLT Terrain
☒ VVA: Forested
☐ NVA: Urban Areas
☐ NGS Control

PICTURES

☑ Picture(s) of Area & Setup

POINT RE-CHECK

Date: 3-28-2017 Time: 12:42 ☐ a.m. ☒ p.m.
Re-Check Point ID: VVA-249CK
Description of Point:
NAIL SET IN LOW TREES

Sketch Area (NTS)

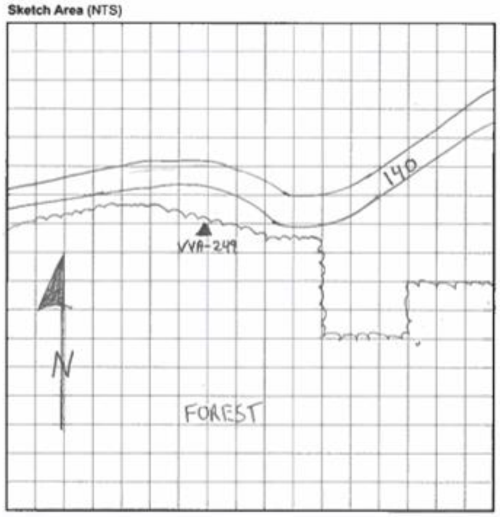


Figure 29 – VVA-249 Check Point Documentation Report

Figure 30 – VVA-249 Survey photos showing the location of the point.

Dewberry CHECK POINT DOCUMENTATION REPORT

Date: 3-29-2019 Time: 8:02 ☒ a.m. ☐ p.m. Employee Name: DAVID JAMESON

Job Name: PR/VI Hurricane Maria Imagery and LiDAR CP Point ID: VVA-621

State: PR Latitude: ______ ☐+ ☐– Longitude: ______ ☐+ ☐–

Address and/or Intersection: ______

OBSERVATION METHOD

☒ VRS GPS	RMS: ___ H: ___ V: ___ Duration: 3 MIN
☐ STATIC GPS	(20 min.) Start Time: ___ ☐ a.m. ☐ p.m. End Time: ___ ☐ a.m. ☐ p.m.
☐ Conventional Pairs VRS	Point Number: ___ RMS: ___ H: ___ V: ___ Duration: ___ Point Number: ___ RMS: ___ H: ___ V: ___ Duration: ___
☐ Conventional Pairs STATIC	(20 min.) Point Number: ___ Start Time: ___ ☐ a.m. ☐ p.m. End Time: ___ ☐ a.m. ☐ p.m. Point Number: ___ Start Time: ___ ☐ a.m. ☐ p.m. End Time: ___ ☐ a.m. ☐ p.m.
☐ Occupied Point	Pt. #/HT: ___/___ ☐ BS Pt. #/HT ___/___ ☐ FS Pt. #/HT ___/___
☐ Back Site Point	Distance: ___ Vertical Angle: ___ ☐ Angle 00°00'00"
☐ FS Point	Angle: ___ Vertical Angle: ___ Slope Distance: ___ Horizontal Distance: ___

TYPE OF CHECK POINT

- ☐ NVA: OPEN Terrain
- ☐ VVA: GWC Terrain
- ☐ VVA: BLT Terrain
- ☒ VVA: Forested
- ☐ NVA: Urban Areas
- ☐ NGS Control

PICTURES

- ☑ Picture(s) of Area & Setup

POINT RE-CHECK

Date: 4-6-2019 Time: 10:00 ☒ a.m. ☐ p.m.

Re-Check Point ID: VVA-621 RC

Description of Point: NAIL SET ON FLAT FORESTED AREA

Sketch Area (NTS)

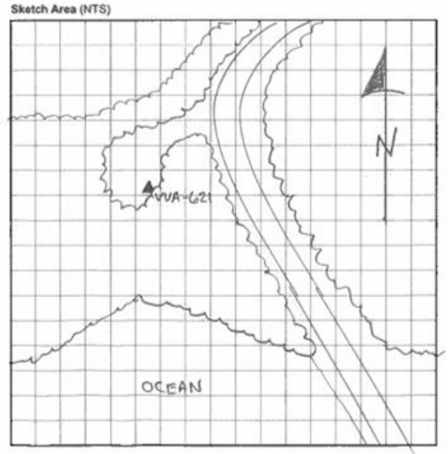


Figure 31 – VVA-621 Check Point Documentation Report

Figure 32 – VVA-621 Survey photos showing the location of the point.

The figure below shows the location of the QA/QC checkpoints used to test the positional accuracy of the dataset.

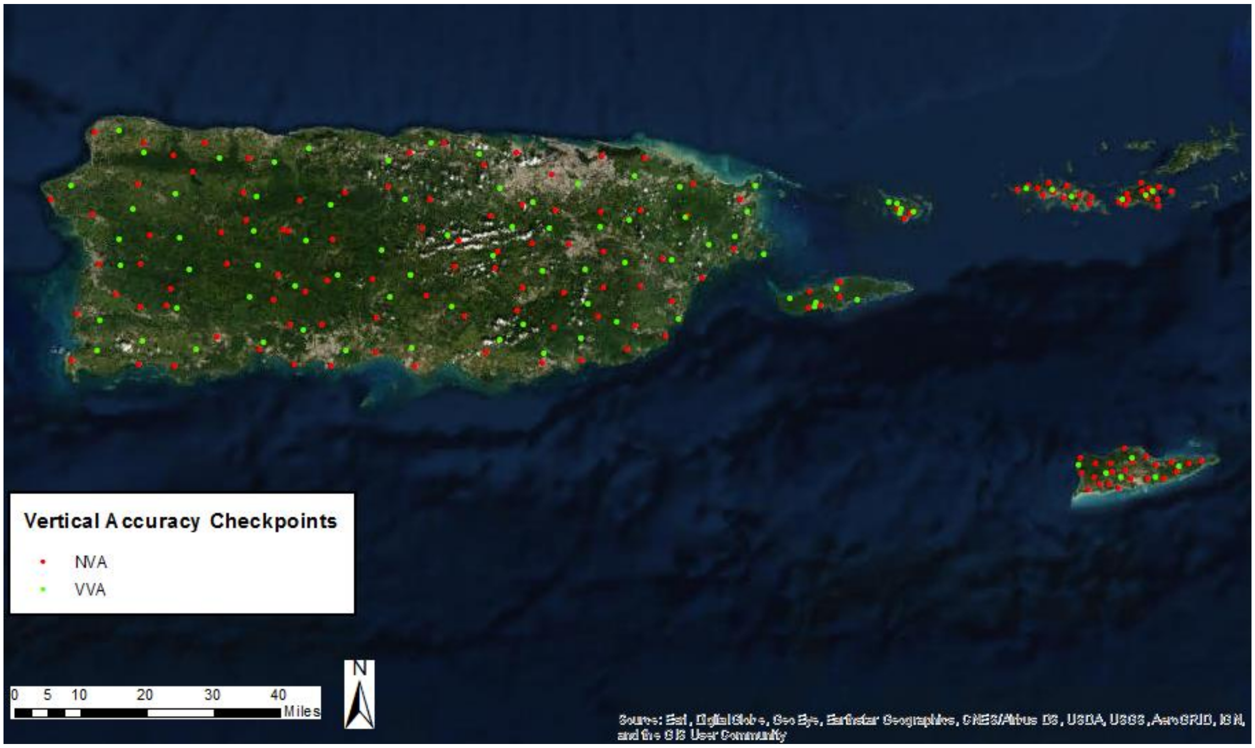


Figure 33 – Location of QA/QC Checkpoints

VERTICAL ACCURACY TEST PROCEDURES

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 ($RMSE_z$) of the checkpoints x 1.9600. For the PR USVI 2018 Lidar project, vertical accuracy must be 19.6 cm or less based on an $RMSE_z$ of 10 cm x 1.9600.

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 PR USVI 2018 Lidar project VVA standard is 29.4 cm based on the 95th percentile. The VVA is accompanied by a listing of the 5% outliers that are larger than the 95th percentile used to compute the VVA; these are always the largest outliers that may depart from a normal error distribution. 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 17.

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	29.4 cm (based on combined 95th percentile)

Table 17 – Acceptance Criteria

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

1. Dewberry's team surveyed QA/QC vertical checkpoints in accordance with the project's specifications.
2. Next, Dewberry interpolated the bare-earth lidar DTM to provide the z-value for every checkpoint.
3. Dewberry 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 Dewberry 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

The tables below summarize the tested vertical accuracy resulting from a comparison of the surveyed checkpoints to the elevation values present within the fully classified lidar LAS files. For the purposes of accuracy testing, the project was divided into three areas in order to ensure all areas were tested appropriately for vertical accuracy. As such, the island of Puerto Rico and its surrounding island was tested as one area, St. Croix was tested as one area, and St. John and St. Thomas were tested as one area.

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	96	13.2	
VVA	71		27.0

Table 18 – The island of Puerto Rico and its surrounding islands tested NVA and VVA

The island of Puerto Rico and its surrounding islands were 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 $RMSE_z$ =6.8 cm, equating to +/- 13.2 cm at 95% confidence level. Actual VVA accuracy was found to be +/- 27.0 cm at the 95th percentile.

The figure below illustrates the magnitude of the differences between the QA/QC checkpoints and lidar data. This shows that the majority of lidar elevations were within +/- 30 cm of the checkpoints elevations, but there were some outliers where lidar and checkpoint elevations differed by up to +40 cm.

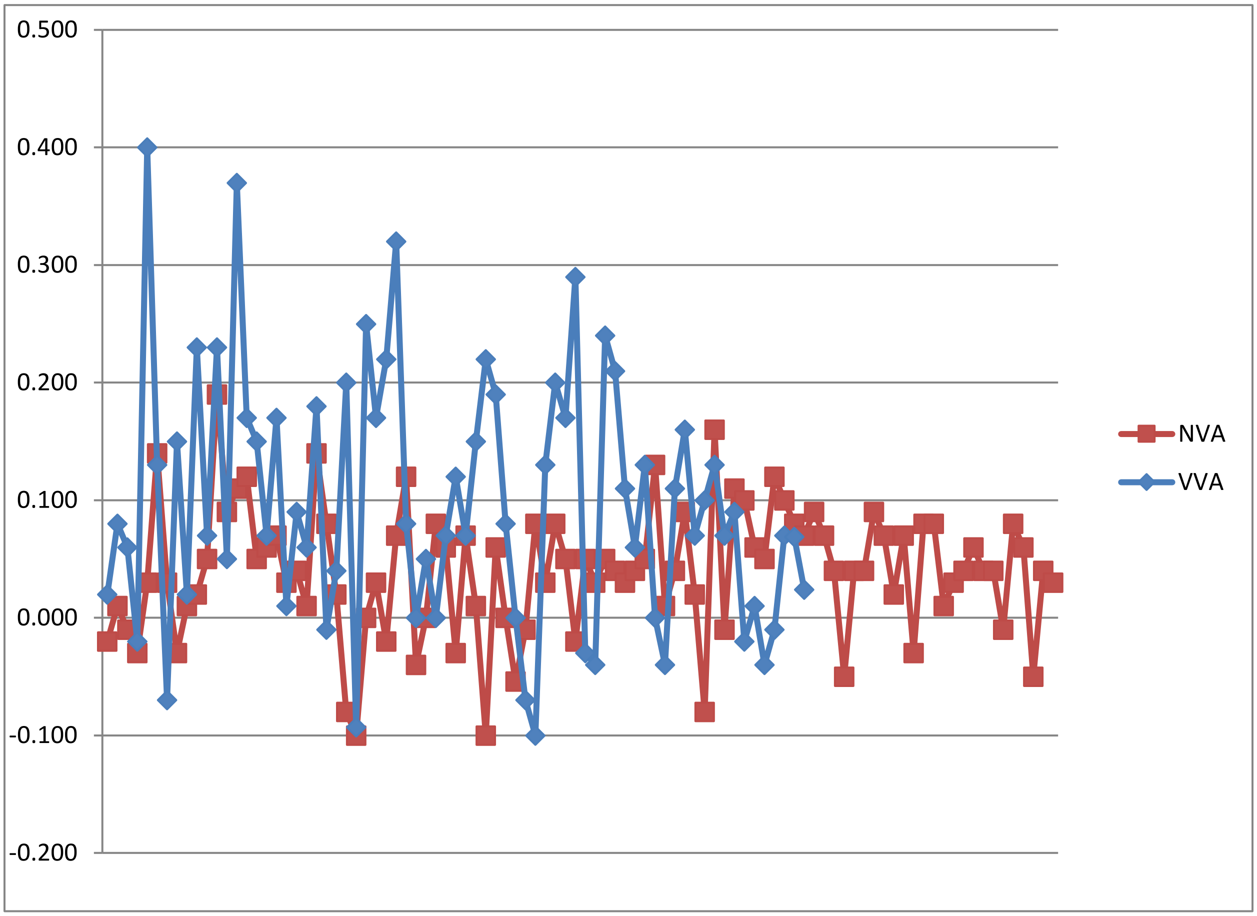


Figure 34 – Magnitude of elevation discrepancies per land cover category

Table 19 lists the 5% outliers that are larger than the VVA 95th percentile.

Point ID	NAD83(2011) UTM Zone 18N		NAVD88 (Geoid 12B)	Lidar Z (m)	Delta Z	AbsDeltaZ
	Easting X (m)	Northing Y (m)	Survey Z (m)			
VVA-005	320160.980	252243.840	4.910	5.310	0.400	0.400
VVA-014	241995.830	259543.030	51.700	52.070	0.370	0.370
VVA-034	183439.760	237259.680	1141.720	1142.040	0.320	0.320
VVA-052	223109.330	258303.200	54.880	55.170	0.290	0.290

Table 19 — 5% Outliers

The figure below illustrates a histogram of the associated elevation discrepancies between the QA/QC checkpoints and elevations interpolated from the lidar triangulated irregular network (TIN). The frequency shows the number of discrepancies within each band of elevation differences. Although the discrepancies vary between a low of -0.1 meters and a high of +0.4 meters, the histogram shows that the majority of the discrepancies are skewed on the positive side. The vast majority of points are within the ranges of -0.035 meters to +0.105 meters.

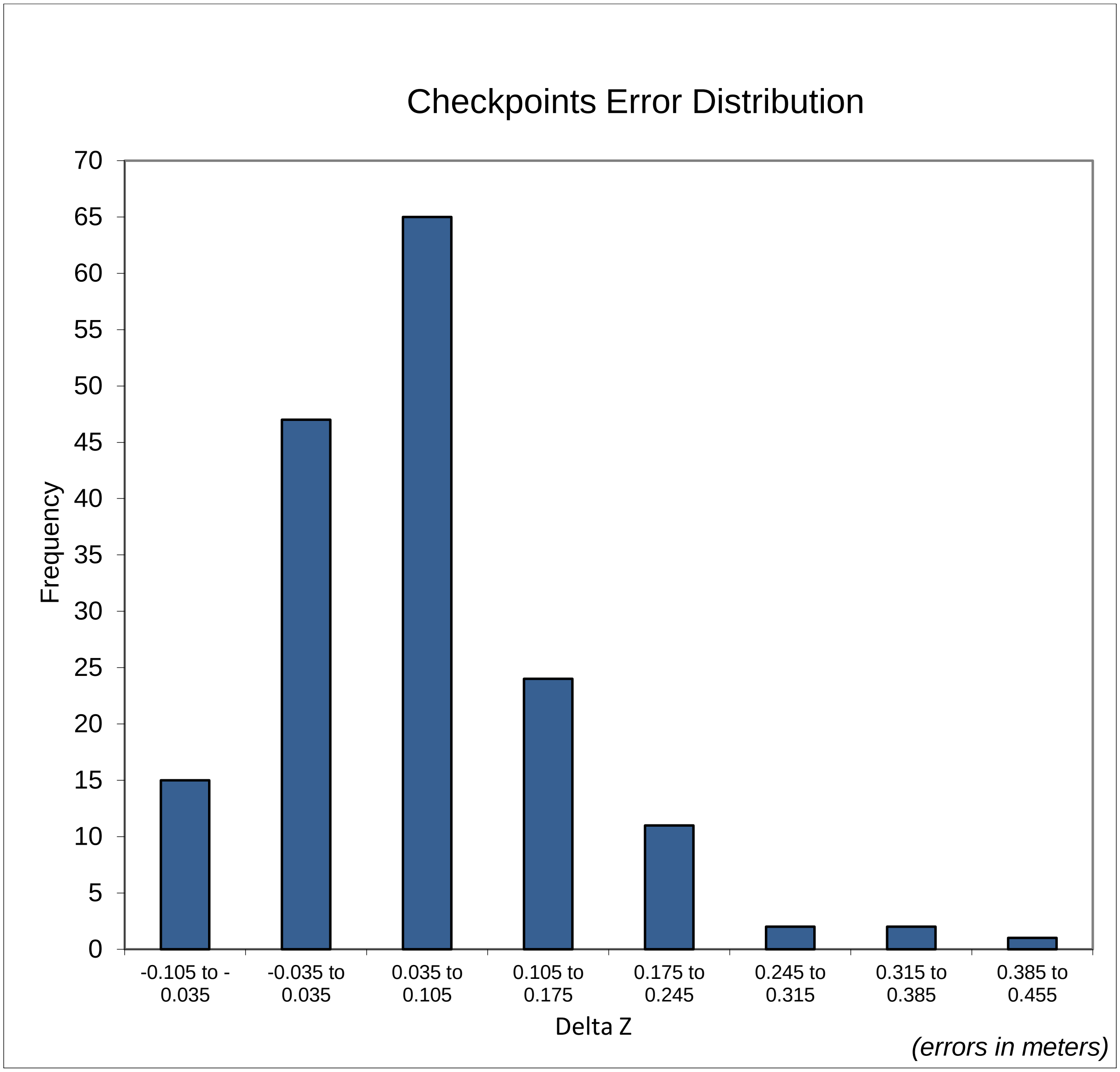


Figure 35 – Histogram of Elevation Discrepancies with errors in meters

Based on the vertical accuracy testing conducted by Dewberry, the island of Puerto Rico and its surrounding islands lidar dataset for the USGS PR USVI 2018 Lidar Project satisfies the project's pre-defined vertical accuracy criteria.

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	22	12.9	

VVA	6		9.5

Table 20 — St. Croix tested NVA and VVA

St. Croix 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 $RMSE_z$ =6.6 cm, equating to +/- 12.9 cm at 95% confidence level. Actual VVA accuracy was found to be +/- 9.5 cm at the 95th percentile.

The figure below illustrates the magnitude of the differences between the QA/QC checkpoints and lidar data. This shows that the majority of lidar elevations were within +/- 20 cm of the checkpoints elevations, but there were some outliers where lidar and checkpoint elevations differed by up to +17 cm.

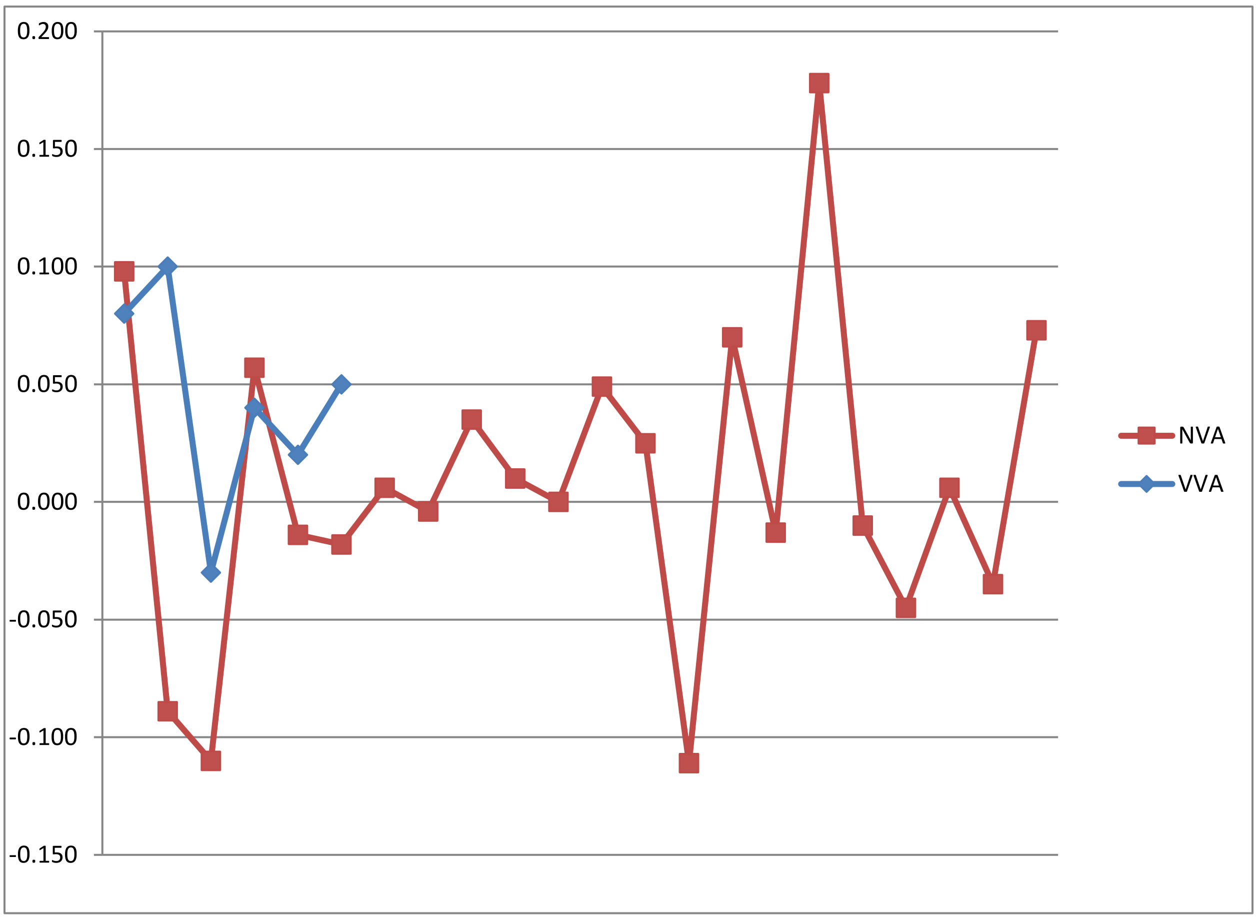


Figure 36 – Magnitude of elevation discrepancies per land cover category

Table 21 lists the 5% outliers that are larger than the VVA 95th percentile.

Point ID	NAD83(2011) UTM Zone 18N	NAVD88 (Geoid 12B)	Lidar Z (m)	Delta Z	AbsDeltaZ

	Easting X (m)	Northing Y (m)	Survey Z (m)			
VVA-081	370239.230	189236.710	76.980	77.080	0.100	0.100

Table 21 — 5% Outliers

The figure below illustrates a histogram of the associated elevation discrepancies between the QA/QC checkpoints and elevations interpolated from the lidar triangulated irregular network (TIN). The frequency shows the number of discrepancies within each band of elevation differences. Although the discrepancies vary between a low of -0.11 meters and a high of +0.18 meters, the histogram shows that the majority of the discrepancies are skewed on the positive side. The vast majority of points are within the ranges of -0.025 meters to +0.025 meters.

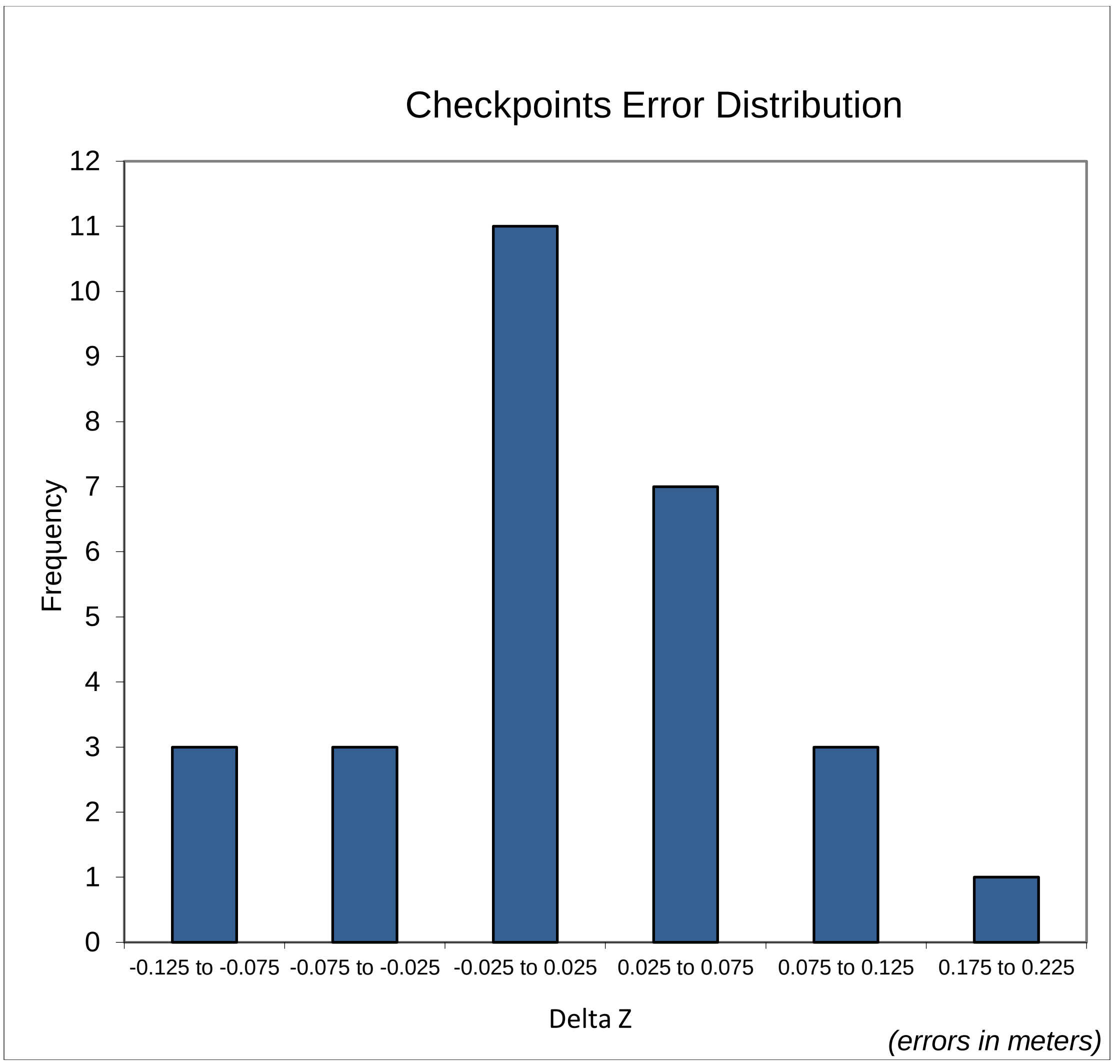


Figure 37 — Histogram of Elevation Discrepancies with errors in meters

Based on the vertical accuracy testing conducted by Dewberry, the St. Croix lidar dataset for the USGS PR USVI 2018 Lidar Project satisfies the project's pre-defined vertical accuracy criteria.

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	26	10.2	
VVA	6		11.1

Table 22 – St. John and St. Thomas tested NVA and VVA

St. John and St. Thomas were 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 $RMSE_z$ =5.2 cm, equating to +/- 10.2 cm at 95% confidence level. Actual VVA accuracy was found to be +/- 11.1 cm at the 95th percentile.

The figure below illustrates the magnitude of the differences between the QA/QC checkpoints and lidar data. This shows that the majority of lidar elevations were within +/- 10 cm of the checkpoints elevations, but there were some outliers where lidar and checkpoint elevations differed by up to +12 cm.

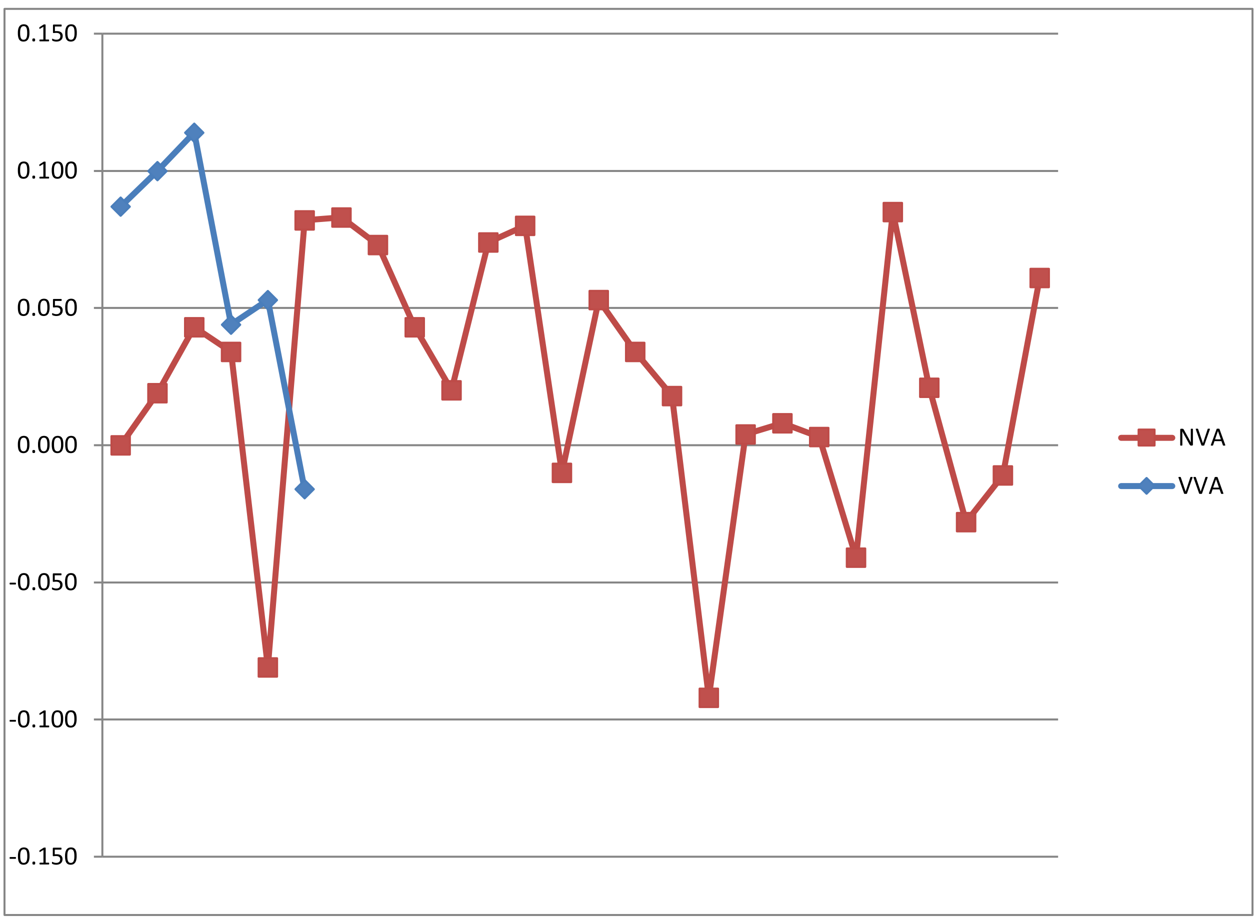


Figure 38 – Magnitude of elevation discrepancies per land cover category

Table 23 lists the 5% outliers that are larger than the VVA 95th percentile.

Point ID	NAD83(2011) UTM Zone 18N		NAVD88 (Geoid 12B)	Lidar Z (m)	Delta Z	AbsDeltaZ
	Easting X (m)	Northing Y (m)	Survey Z (m)			
VVA-076	361879.303	256246.998	76.426	76.540	0.114	0.114

Table 23 – 5% Outliers

The figure below illustrates a histogram of the associated elevation discrepancies between the QA/QC checkpoints and elevations interpolated from the lidar triangulated irregular network (TIN). The frequency shows the number of discrepancies within each band of elevation differences. Although the discrepancies vary between a low of -0.09 meters and a high of +0.11 meters, the histogram shows that the majority of the discrepancies are skewed on the positive side. The vast majority of points are within the ranges of -0.02 meters to +0.06 meters.

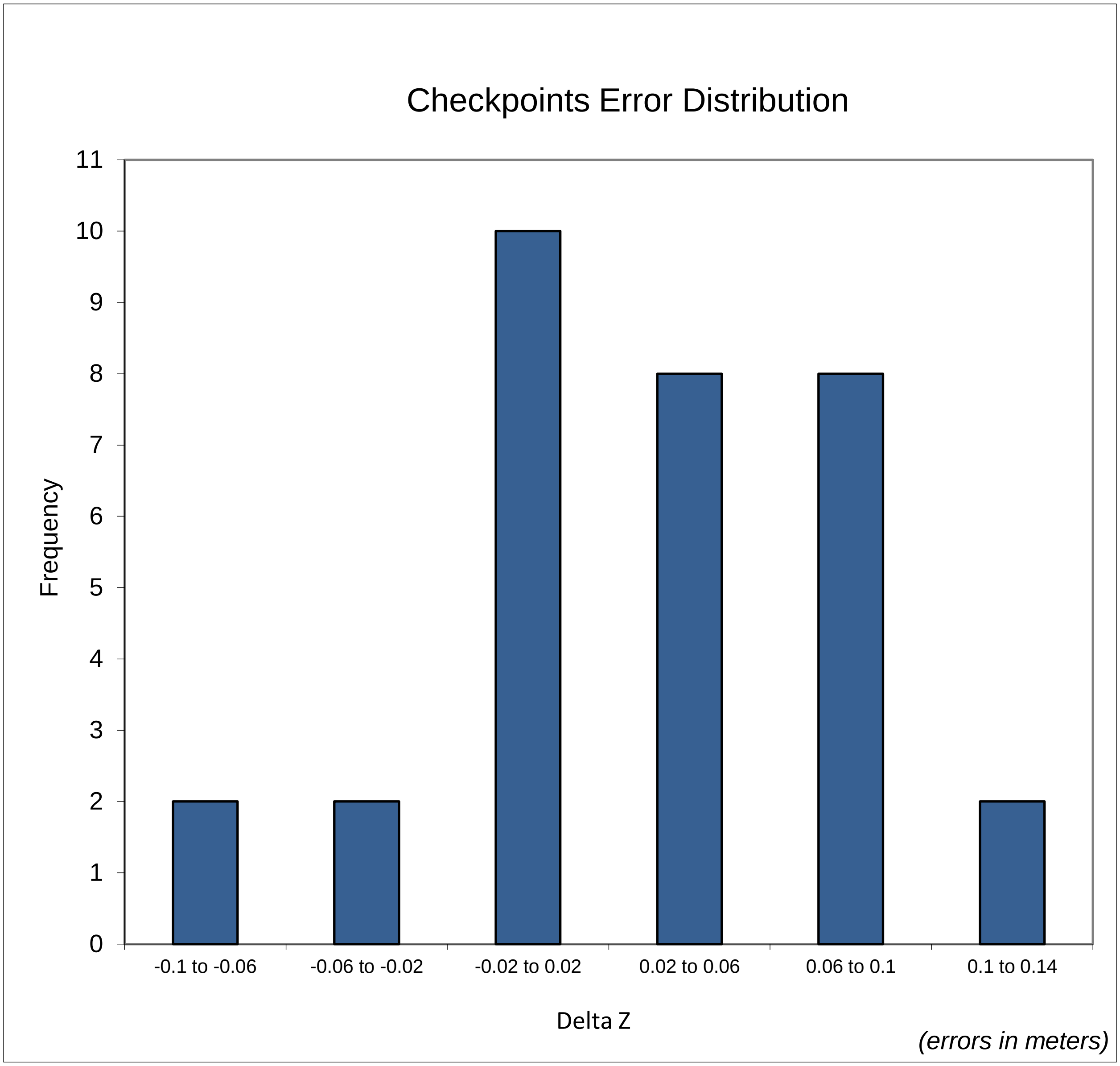


Figure 39 – Histogram of Elevation Discrepancies with errors in meters

Based on the vertical accuracy testing conducted by Dewberry, the St. John and St. Thomas lidar dataset for the USGS PR USVI 2018 Lidar Project satisfies the project's pre-defined vertical accuracy criteria.

HORIZONTAL ACCURACY TEST PROCEDURES

Horizontal accuracy testing requires well-defined checkpoints that can be identified in the dataset. Elevation datasets, including lidar datasets, do not always contain well-defined checkpoints suitable for horizontal accuracy assessment. However, the ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) recommends at least half of the NVA vertical check points should be located at the ends of paint stripes or other point features visible on the lidar intensity image, allowing them to double as horizontal check points.

Dewberry reviews all NVA checkpoints to determine which, if any, of these checkpoints are located on photo-identifiable features in the intensity imagery. This subset of checkpoints are then used for horizontal accuracy testing.

The primary QA/QC horizontal accuracy testing steps used by Dewberry are summarized as follows:

1. Dewberry's team surveyed QA/QC vertical checkpoints in accordance with the project's specifications and tried to locate half of the NVA checkpoints on features photo-identifiable in the intensity imagery.
2. Next, Dewberry identified the well-defined features in the intensity imagery.
3. Dewberry then computed the associated xy-value differences between the coordinates of the well-defined feature in the lidar intensity imagery and the ground truth survey checkpoints.
4. The data were analyzed by Dewberry to assess the accuracy of the data. Horizontal accuracy was assessed using NSSDA methodology where horizontal accuracy is calculated at the 95% confidence level. This report provides the results of the horizontal accuracy testing.

HORIZONTAL ACCURACY RESULTS

For the island of Puerto Rico and its surrounding islands, seventeen (17) checkpoints were determined to be photo-identifiable in the intensity imagery and were used to test the horizontal accuracy of the lidar dataset. As only seventeen (17) checkpoints were photo-identifiable, the results are not statistically significant enough to report as a final tested value, but the results of the testing are still shown in the Table below.

Using NSSDA methodology (endorsed by the ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014)), horizontal accuracy at the 95% confidence level (called ACCURACYr) is computed by the formula RMSEr * 1.7308 or RMSExy * 2.448.

No horizontal accuracy requirements or thresholds were provided for this project. However, lidar datasets are generally calibrated by methods designed to ensure a horizontal accuracy of 1 meter or less at the 95% confidence level.

# of Points	$RMSE_x$ (Target=41 cm)	$RMSE_y$ (Target=41 cm)	$RMSE_r$ (Target=58 cm)	$ACCURACY_r$ ($RMSE_r$ x 1.7308) Target=100 cm
17	15.5	12.2	19.7	34.1

Table 24 - Tested horizontal accuracy at the 95% confidence level

The island of Puerto Rico and its surrounding islands were produced to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 41 cm RMSEx/RMSEy Horizontal Accuracy Class which equates to Positional Horizontal Accuracy = +/- 1 meter at a 95% confidence level. Seventeen (17) checkpoints were photo-identifiable but do not produce a statistically significant tested horizontal accuracy value. Using this small sample set of photo-identifiable checkpoints, positional accuracy of this dataset was found to be RMSEx = 15.5 cm and RMSEy = 12.2 cm which equates to +/- 34.1 cm at 95% confidence level. While not statistically significant, the results of the small sample set of checkpoints are within the produced to meet horizontal accuracy.

For St. Croix, one (1) checkpoint was determined to be photo-identifiable in the intensity imagery and were used to test the horizontal accuracy of the lidar dataset. As only one (1) checkpoint was photo-identifiable, the results are not statistically significant enough to report as a final tested value, but the results of the testing are still shown in the table below.

Using NSSDA methodology (endorsed by the ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014)), horizontal accuracy at the 95% confidence level (called ACCURACYr) is computed by the formula RMSEr * 1.7308 or RMSExy * 2.448.

No horizontal accuracy requirements or thresholds were provided for this project. However, lidar datasets are generally calibrated by methods designed to ensure a horizontal accuracy of 1 meter or less at the 95% confidence level.

# of Points	$RMSE_x$ (Target=41 cm)	$RMSE_y$ (Target=41 cm)	$RMSE_r$ (Target=58 cm)	$ACCURACY_r$ ($RMSE_r$ x 1.7308) Target=100 cm
1	43.7	26.0	50.9	88.1

Table 25 - Tested horizontal accuracy at the 95% confidence level

St. Croix was produced to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 41 cm RMSEx/RMSEy Horizontal Accuracy Class which equates to Positional Horizontal Accuracy = +/- 1 meter at a 95% confidence level. One (1) checkpoint was photo-identifiable but does not produce a statistically significant tested horizontal accuracy value. Using this small sample set of photo-identifiable checkpoints, positional accuracy of this dataset was found to be RMSEx = 43.7 cm and RMSEy = 26.0 cm which equates to +/- 88.1 cm at 95% confidence level. While not statistically significant, the results of the small sample set of checkpoints are within the produced to meet horizontal accuracy.

For St. John and St. Thomas, five (5) checkpoints were determined to be photo-identifiable in the intensity imagery and were used to test the horizontal accuracy of the lidar dataset. As only five (5) checkpoints were photo-identifiable, the results are not statistically significant enough to report as a final tested value, but the results of the testing are still shown in the table below.

Using NSSDA methodology (endorsed by the ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014)), horizontal accuracy at the 95% confidence level (called ACCURACYr) is computed by the formula RMSEr * 1.7308 or RMSExy * 2.448.

No horizontal accuracy requirements or thresholds were provided for this project. However, lidar datasets are generally calibrated by methods designed to ensure a horizontal accuracy of 1 meter or less at the 95% confidence level.

# of Points	$RMSE_x$ (Target=41 cm)	$RMSE_y$ (Target=41 cm)	$RMSE_r$ (Target=58 cm)	$ACCURACY_r$ ($RMSE_r$ x 1.7308) Target=100 cm
5	21.9	10.9	24.4	42.3

Table 26 - Tested horizontal accuracy at the 95% confidence level

St. John and St. Thomas were produced to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 41 cm RMSEx/RMSEy Horizontal Accuracy Class which equates to Positional Horizontal Accuracy = +/- 1 meter at a 95% confidence level. Five (5) checkpoints were photo-identifiable but do not produce a statistically significant tested horizontal accuracy value. Using this small sample set of photo-identifiable checkpoints, positional accuracy of this dataset was found to be RMSEx = 21.9 cm and RMSEy = 10.9 cm which equates to +/- 42.3 cm at 95% confidence level. While not statistically significant, the results of the small sample set of checkpoints are within the produced to meet horizontal accuracy.

Breakline Production & Qualitative Assessment Report

BREAKLINE PRODUCTION METHODOLOGY

Dewberry used a combination of lidargrammetry and automated processing to collect 3D breaklines for this project. The delineation of lakes, ponds, and tidal waters, and other water bodies at a constant elevation was achieved using ArcMap software. Dewberry produced intensity imagery, bare earth ground models, and terrain datasets that were reviewed to delineate the water features. Once the horizontal position of each breakline was validated, 3D elevations were applied to each feature using automated techniques.

All drainage breaklines are monotonically enforced to show downhill flow. Water bodies are at a constant elevation where the lowest elevation of the water body has been applied to the entire water body.

BREAKLINE QUALITATIVE ASSESSMENT

Dewberry completed breakline qualitative assessments according to a defined workflow. The following workflow diagram represents the steps taken by Dewberry to provide a thorough qualitative assessment of the breakline data.

Completeness and horizontal placement is 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.

The next step is to compare the elevation of the breakline vertices against the ground elevation extracted from the ESRI Terrain built from the lidar ground points, keeping in mind that a discrepancy is expected because of the hydro-enforcement applied to the breaklines and because of the interpolated imagery used to acquire the breaklines. A given tolerance is used to validate if the elevations differ too much from the lidar.

After all corrections and edits to the breakline features, the breaklines are imported into the final GDB and verified for correct formatting.

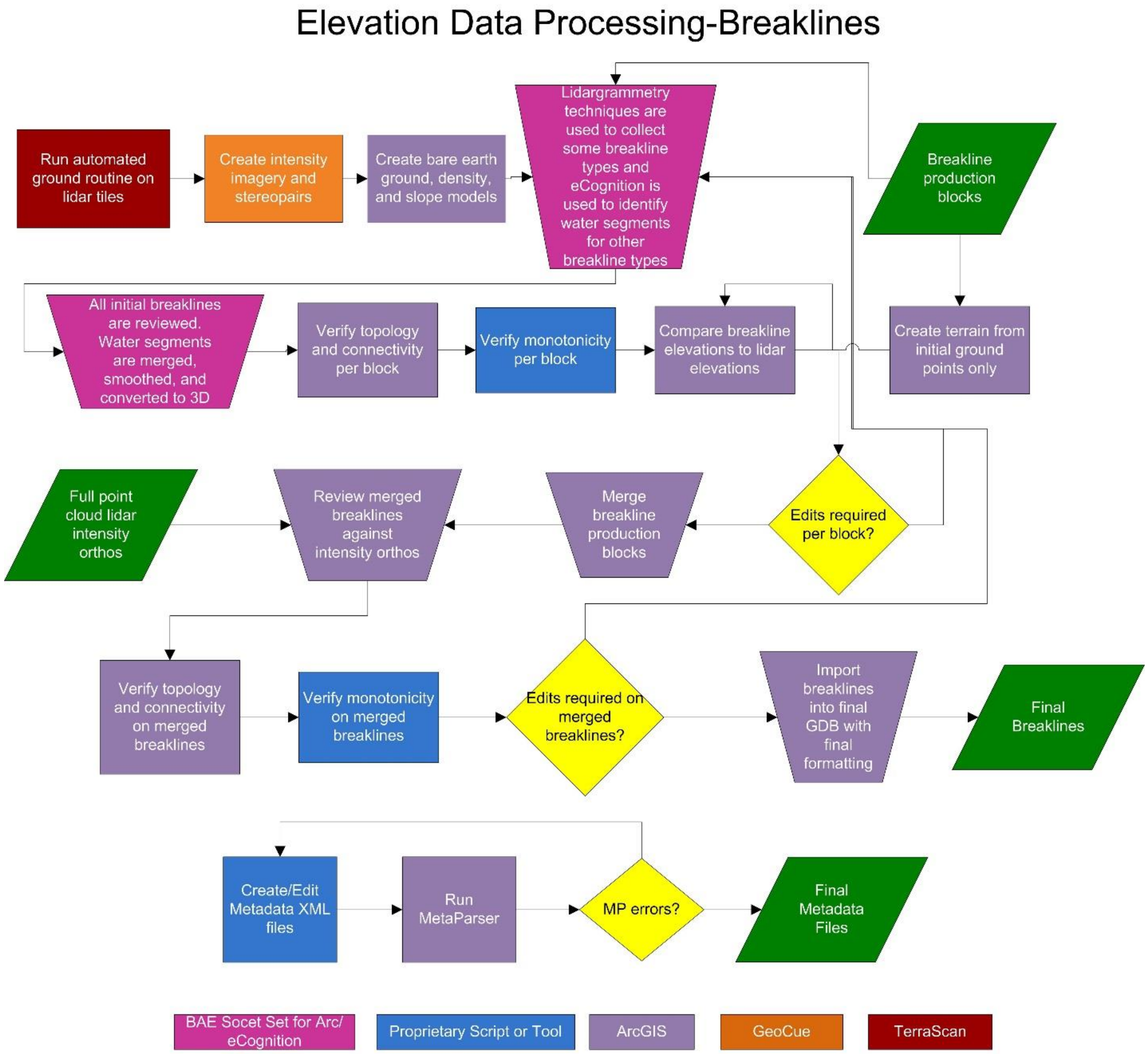


Figure 40 - Breakline QA/QC workflow

BREAKLINE CHECKLIST

The following table represents a portion of the high-level steps in Dewberry's Production and QA/QC checklist that were performed for this project.

Pass/Fail	Validation Step
Pass	Use lidar-derived data, which may include intensity imagery, stereo pairs, bare earth ground models, density models, slope models, and terrains, to collect breaklines according to project specifications.
Pass	In areas of heavy vegetation or where the exact shoreline is hard to delineate, it is better to err on placing the breakline *slightly* inside or seaward of the shoreline (breakline can be inside shoreline by 1x-2x NPS).

Pass	After each producer finishes breakline collection for a block, each producer must perform a completeness check, breakline variance check, and all automated checks on their block before calling that block complete and ready for the final merge and QC
Pass	After breaklines are completed for production blocks, all production blocks should be merged together and completeness and automated checks should be performed on the final, merged GDB. Ensure correct snapping-horizontal (x,y) and vertical (z)-between all production blocks.
Pass	Check entire dataset for missing features that were not captured, but should be to meet baseline specifications or for consistency. Features should be collected consistently across tile bounds. Check that the horizontal placement of breaklines is correct. Breaklines should be compared to full point cloud intensity imagery and terrains
Pass	Breaklines are correctly edge-matched to adjoining datasets in completion, coding, and horizontal placement.
Pass	Using a terrain created from lidar ground (all ground including 2, 8, and 10) and water points (class 9), compare breakline Z values to interpolated lidar elevations.
Pass	Perform all Topology and Data Integrity Checks
Pass	Perform hydro-flattening and hydro-enforcement checks including monotonicity and flatness from bank to bank on linear hydrographic features and flatness of water bodies. Tidal waters should preserve as much ground as possible and can include variations or be non-monotonic.

Table 27 - A subset of the high-level steps from Dewberry's Production and QA/QC checklist performed for this project.

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), Units in Meters. The vertical datum shall be referenced to the Puerto Rico Vertical Datum of 2002 (PRVD02) and Virgin Islands Vertical Datum 2009 (VIVD09) , Units in Meters. Geoid12B shall be used to convert ellipsoidal heights to orthometric heights.

Coordinate System and Projection

All data shall be projected to State Plane Coordinate System, Puerto Rico USVI Zone 5200, Horizontal Units in Meters and Vertical Units in Meters.

Inland Streams and Rivers

Feature Dataset: BREAKLINES
Feature Type: Polygon
Contains Z Values: Yes
XY Resolution: Accept Default Setting
XY Tolerance: 0.003

Feature Class: STREAMS_AND_RIVERS
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
SHAPE_AREA	Double	Yes			0	0		Calculated by Software

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 in order to allow for the island feature to remain as a "hole" in the feature.

Inland Ponds and Lakes

Feature Dataset: BREAKLINES
Feature Type: Polygon
Contains Z Values: Yes
XY Resolution: Accept Default Setting
XY Tolerance: 0.003

Feature Class: PONDS_AND_LAKES
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 and greater than 2 acres.

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
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.

Tidal Waters

Feature Dataset: BREAKLINES
Feature Type: Polygon
Contains Z Values: Yes
XY Resolution: Accept Default Setting
XY Tolerance: 0.003

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

Description

This polygon feature class will outline the land / water interface at the time of lidar acquisition.

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
SHAPE_AREA	Double	Yes			0	0		Calculated by Software

Feature Definition

Description	Definition	Capture Rules
TIDAL_WATERS	The coastal breakline will delineate the land water interface using lidar data as reference. In flight line boundary areas with tidal variation the coastal shoreline may show stair stepping as no feathering is allowed. Stair stepping is allowed to show as much ground as the collected data permits.	The feature shall be extracted at the apparent land/water interface, as determined by the lidar intensity data, to the extent of the tile boundaries. Differences caused by tidal variation are acceptable and breaklines delineated should reflect that change with no feathering. 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. 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. Breaklines shall snap and merge seamlessly with linear hydrographic features.

Beneath Bridge Breaklines

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

Description

This polyline feature class is used to enforce terrain beneath bridge decks where ground data may not have been acquired. Enforcing the terrain beneath bridge decks prevents bridge saddles.

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

Feature Definition

Description	Definition	Capture Rules
Bridge Breaklines	Bridge Breaklines should be used where necessary to enforce terrain beneath bridge decks and to prevent bridge saddles in the bare earth DEMs.	Bridge breaklines should be collected beneath bridges where bridge saddles exist or are likely to exist in the bare earth DEMs. Bridge breaklines should be collected perpendicular to the bridge deck so that the endpoints are on either side of the bridge deck. Typically two bridge breaklines are collected per bridge deck, one at either end of the bridge deck to enforce the terrain under the full bridge deck. The endpoints of the bridge breaklines will match the elevation of the ground at their xy position to enforce the ground/bare earth elevations beneath the bridge deck and prevent bridge saddles from forming.

DEM Production & Qualitative Assessment

DEM PRODUCTION METHODOLOGY

Dewberry utilized ESRI software and Global Mapper for the DEM production and QC process. ArcGIS software is used to generate the products and the QC is performed in both ArcGIS and Global Mapper. The figure below shows the entire process necessary for bare earth DEM production, starting from the lidar swath processing.

The final bare-earth lidar points are used to create a terrain. The final 3D breaklines collected for the project are also enforced in the terrain. The terrain is then converted to raster format using linear interpolation. For most projects, a single terrain/DEM can be created for the whole project. For very large projects, multiple terrains/DEMs may be created. The DEM(s) is reviewed for any issues requiring corrections, including remaining lidar mis-classifications, erroneous breakline elevations, poor hydro-flattening or hydro-enforcement, and processing artifacts. After corrections are applied, the DEM(s) is then split into individual tiles following 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.

Figure 41 - DEM Production Workflow

DEM QUALITATIVE ASSESSMENT

Dewberry 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 Dewberry 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 Dewberry creates HillShade models and overlays a partially transparent colorized elevation model to review for these issues. All corrections are completed using Dewberry'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.

The images below show an example of a bare earth DEM of the same tile.

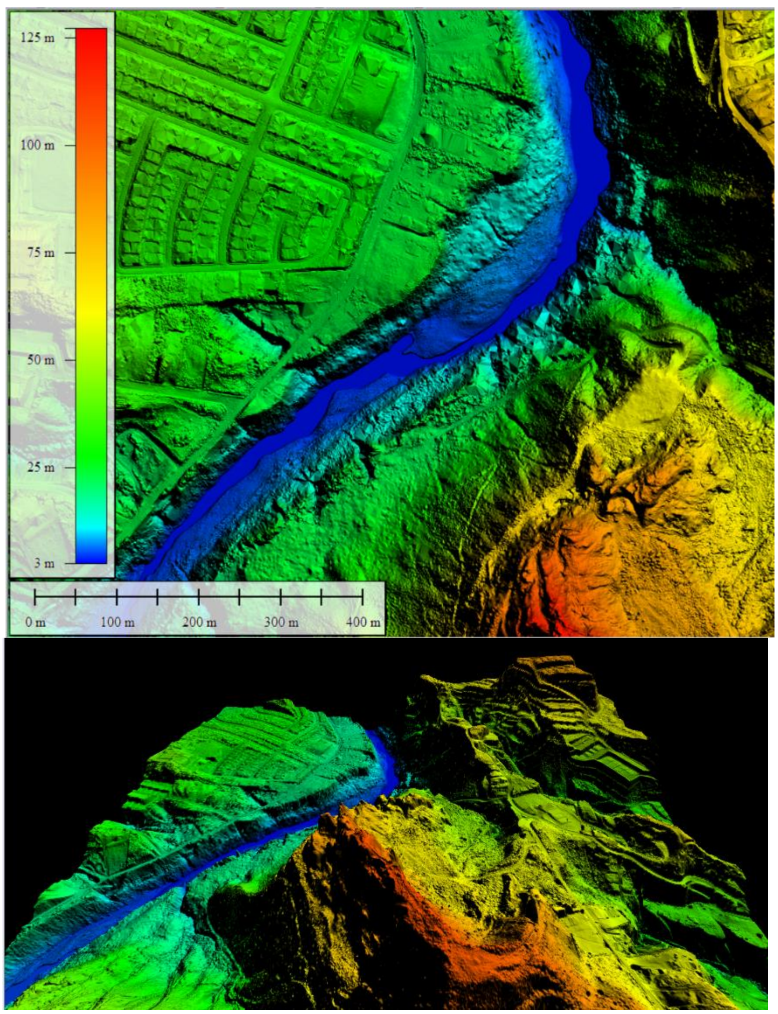


Figure 42 - Tile 19QHA45005550. Top view: Bare earth DEM. Bottom view: 3D profile of DEM.

When some bridges are removed from the ground surface, the distance from bridge abutment to bridge abutment is small enough that the DEM interpolates across the entire bridge opening, forming 'bridge saddles.' Dewberry collected 3D bridge breaklines in locations where bridge saddles were present and enforced these breaklines in the final DEM creation to help mitigate the bridge saddle artifacts. The image below on the left shows a bridge saddle while the image below on the right shows the same bridge after bridge breaklines have been enforced.

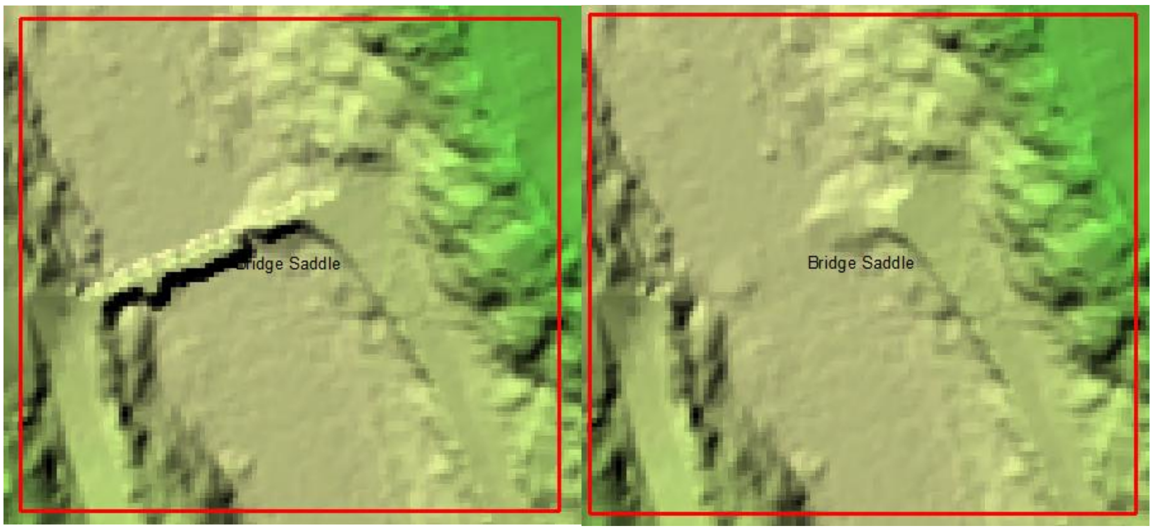


Figure 43 – Tile 19QGA68504350. The image on the left is an overview of the DEM where USGS made a bridge saddle call. The image on the right shows the corrected DEM.

DEM VERTICAL ACCURACY RESULTS

The same 232 checkpoints that were used to test the vertical accuracy of the lidar were used to validate the vertical accuracy of the final DEM products as well. Accuracy results may vary between the source lidar and final DEM deliverable. DEMs are created by averaging several lidar points within 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 two or 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. Dewberry typically uses LP360 software to test the swath lidar vertical accuracy, Terrascan software to test the classified lidar vertical accuracy, and Esri ArcMap to test the DEM vertical accuracy so that three different software programs are used to validate the vertical accuracy for each project.

Table 28 summarizes the tested vertical accuracy results from a comparison of the surveyed checkpoints to the elevation values present within the final island of Puerto Rico and its surrounding islands 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=29.4 cm

NVA	96	13.4	
VVA	71		27.3

Table 28 – 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 $RMSE_z$ =6.8 cm, equating to +/- 13.4 cm at 95% confidence level. Actual VVA accuracy was found to be +/- 27.3 cm at the 95th percentile.

Table 29 lists the 5% outliers that are larger than the VVA 95th percentile.

Point ID	NAD83(2011) UTM Zone 18N		NAVD88 (Geoid 12B)	DEM Z (m)	Delta Z	AbsDeltaZ
	Easting X (m)	Northing Y (m)	Survey Z (m)			
VVA-005	320160.980	252243.840	4.910	5.308	0.398	0.398
VVA-014	241995.830	259543.030	51.700	52.031	0.331	0.331
VVA-034	183439.760	237259.680	1141.720	1142.019	0.299	0.299
VVA-052	223109.330	258303.200	54.880	55.171	0.291	0.291

Table 29 – 5% Outliers

Based on the vertical accuracy testing conducted by Dewberry, the island of Puerto Rico and its surrounding islands DEM dataset for the PR USVI 2018 Lidar Project satisfies the project's pre-defined vertical accuracy criteria.

Table 30 summarizes the tested vertical accuracy results from a comparison of the surveyed checkpoints to the elevation values present within the final St. Croix 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=29.4 cm
NVA	22	12.8	
VVA	6		9.4

Table 30 – 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 $RMSE_z$ =6.5 cm, equating to +/- 12.8 cm at 95% confidence level. Actual VVA accuracy was found to be +/- 9.4 cm at the 95th percentile.

Table 31 lists the 5% outliers that are larger than the VVA 95th percentile.

Point ID	NAD83(2011) UTM Zone 18N		NAVD88 (Geoid 12B)	DEM Z (m)	Delta Z	AbsDeltaZ
	Easting X (m)	Northing Y (m)	Survey Z (m)			

VVA-081	370239.230	189236.710	76.980	77.075	0.095	0.095

Table 31 – 5% Outliers

Based on the vertical accuracy testing conducted by Dewberry, the St. Croix DEM dataset for the PR USVI 2018 Lidar Project satisfies the project's pre-defined vertical accuracy criteria.

Table 32 summarizes the tested vertical accuracy results from a comparison of the surveyed checkpoints to the elevation values present within the St. John and St. Thomas 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=29.4 cm
NVA	26	10.3	
VVA	6		11.2

Table 32 – 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 $RMSE_z$ =5.3 cm, equating to +/- 10.3 cm at 95% confidence level. Actual VVA accuracy was found to be +/- 11.2 cm at the 95th percentile.

Table 33 lists the 5% outliers that are larger than the VVA 95th percentile.

Point ID	NAD83(2011) UTM Zone 18N		NAVD88 (Geoid 12B)	DEM Z (m)	Delta Z	AbsDeltaZ
	Easting X (m)	Northing Y (m)	Survey Z (m)			
VVA-076	361879.303	256246.998	76.426	76.542	0.116	0.116

Table 33 – 5% Outliers

Based on the vertical accuracy testing conducted by Dewberry, the St. John and St. Thomas DEM dataset for the PR USVI 2018 Lidar Project satisfies the project's pre-defined vertical accuracy criteria.

DEM CHECKLIST

The following table represents a portion of the high-level steps in Dewberry's bare earth DEM Production and QA/QC checklist that were performed for this project.

Pass/Fail	Validation Step
Pass	Masspoints (LAS to multipoint) are created from ground points only (class 2 and class 8 if model key points created, but no class 10 ignored ground points or class 9 water points
Pass	Create a terrain for each production block using the final bare earth lidar points and final breaklines.
Pass	Convert terrains to rasters using project specifications for grid type, formatting, and cell size

Pass	Create hillshades for all DEMs
Pass	Manually review bare-earth DEMs in ArcMap with hillshades to check for issues
Pass	DEMs should be hydro-flattened or hydro-enforced as required by project specifications
Pass	DEMs should be seamless across tile boundaries
Pass	Water should be flowing downhill without excessive water artifacts present
Pass	Water features should NOT be floating above surrounding
Pass	Bridges should NOT be present in bare-earth DEMs.
Pass	Any remaining bridge saddles where below bridge breaklines were not used need to be fixed by adding below bridge breaklines and re-processing.
Pass	All qualitative issues present in the DEMs as a result of lidar processing and editing issues must be marked for corrections in the lidar These DEMs will need to be recreated after the lidar has been corrected.
Pass	Calculate DEM Vertical Accuracy including NVA, VVA, and other statistics
Pass	Split the DEMs into tiles according to the project tiling scheme
Pass	Verify all properties of the tiled DEMs, including coordinate reference system information, cell size, cell extents, and that compression has not been applied to the tiled DEMs
Pass	Load all tiled DEMs into Global Mapper to verify complete coverage to the (buffered) project boundary and that no tiles are corrupt.

Table 34 - A subset of the high-level steps from Dewberry's bare earth DEM Production and QA/QC checklist performed for this project.

Appendix A: Survey Report

Please see the report included with this deliverable:
Appendix_A_Survey_Report

Appendix B: Ground Control Survey Report

Please see the report included with this deliverable:
Appendix_B_Ground_Control_Survey_Report

Appendix C: Complete List of Delivered Tiles

20QKF34502640
20QKF36002640
20QKF36152640
20QKF34352625
20QKF34502625
20QKF35252625
20QKF35402625
20QKF36002625
20QKF36152625
20QKF34352610
20QKF34502610
20QKF35252610
20QKF35402610
20QKF35702610
20QKF35852610
20QKF36002610
20QKF36152610
20QKF34352595
20QKF34502595
20QKF34952595
20QKF35102595
20QKF35252595
20QKF35402595
20QKF35552595
20QKF35702595
20QKF35852595
20QKF36002595
20QKF36152595
20QLF37052595
20QLF37202595
20QLF37652595
20QLF37802595
20QLF37952595
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Appendix D: GPS Processing

Please see the report included with this deliverable:
Appendix_D_GPS_Processing