Puerto Rico and US Virgin Islands Topobathy Final Report of Survey

Produced for National Oceanic and Atmospheric Administration, Office for Coastal Management

Contract: EA133C-14-CQ-0008

Task Order: Topographic/Bathymetric Data Acquisition on Puerto Rico and the US Virgin Islands

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Produced by:
Dewberry
1000 North Ashley Drive, Suite 801
Tampa, FL 33602
813.225.1325

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Executive Summary

Dewberry was tasked with developing a consistent and accurate topographic and bathymetric (topobathymetric) elevation dataset derived from high-accuracy light detection and ranging (lidar) technology for the National Oceanic and Atmospheric Administration (NOAA) Hurricane Maria post-storm Puerto Rico and United States Virgin Island project area.

The lidar data were processed and classified according to NOAA's Shoreline Mapping Statement of Work (SOW) (Version 14A) and the project instructions for this specific task order. Topobathymetric digital elevation models (DEMs) were produced for the project area. Lidar data were formatted according to tiles with each tile covering an area of 1000 m by 1000 m. A total of 5668 lidar tiles were produced for the project encompassing an area of approximately 1400 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 Simpson completed ground surveying for the project and delivered surveyed checkpoints. His team acquired surveyed checkpoints for the project to use in independent testing of the vertical accuracy of the lidar-derived model. He also verified the GPS base station coordinates used during lidar data acquisition. Survey reports are included as Appendices A and B.

Leading Edge Geomatics, LLC (LEG) completed lidar data acquisition and data calibration for the project area.

PROJECT AREA

The project area addressed by this report covers the coastlines of the commonwealth of Puerto Rico and the US Virgin Islands (figure 1). The total size of the project is approximately 1400 square miles.

Figure 1 – The Puerto Rico and US Virgin Islands Topobathy collection area outlined in yellow.

DATE OF SURVEY

The lidar aerial acquisition was conducted from January 20 through June 02, 2019.

COORDINATE REFERENCE SYSTEM

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

Horizontal Datum: North American Datum of 1983 with the 2011 Adjustment (NAD83(2011))
Vertical Datum: North American Datum of 1983 with the 2011 Adjustment (NAD83(2011), epoch 2010), ellipsoid heights
Coordinate System: UTM Zone 19 and UTM Zone 20
Units: Horizontal units are in meters, Vertical units are in meters.
Geiod Model: Geoid 12B was used to convert ellipsoid heights to orthometric heights

LIDAR VERTICAL ACCURACY

For the Puerto Rico and US Virgin Islands Topobathemetric Lidar Project, the tested $RMSE_z$ of the classified lidar data for checkpoints in non-vegetated terrain is **8.6 cm** compared with the 10 cm specification; and the NVA of the classified lidar data computed using $RMSE_z$ x 1.9600 is equal to **16.8 cm** compared with the 19.6 cm specification.

The tested $RMSE_z$ of the classified lidar data for checkpoints in submerged topography equaled is **12.1 cm** compared with the 18 cm specification; and the Bathymetric Vertical Accuracy of the classified lidar data computed using $RMSE_z$ x 1.9600 is equal to **23.6 cm** compared with the 35.3 cm specification.

The tested VVA of the classified lidar data computed using the 95^{th} percentile is equal to **25.1 cm,** compared with the 29.4 cm specification.

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

PROJECT DELIVERABLES

The deliverables for the project are listed below.

1. Project Extents including boundary and tile grid (shapefiles)
2. Raw swath lidar data (LAS)
3. Final classified lidar tiles (LAS)
4. Refraction extents delineating topographic and bathymetric domains (GDB feature class)
5. Void layer (shapefile)
6. Tiled topobathymetric DEMs with voids enforced (IMG)
7. Tiled standard deviation confidence rasters (IMG)
8. Survey data (various formats)
9. Final Project report (PDF)

OVERVIEW OF CLASSIFICATION

The raw lidar from the bathymetric and topographic sensors were kept in the classes that were outputted by the Reigl processing software. This aided in the classification of the ground and bathymetric bottom. The raw swaths delivered to NOAA were kept in this classification schema and is listed in table 1.

Lidar Classification – Raw Topographic Sensor Data	
Class	**Description**
Class 0	Created, Never Classified
Class 1	Unclassified
Class 20	Water Surface Bayes
Class 41	Water surface
Class 45	Refracted Points
Withheld	Geometrically Unnecessary Points

Table 1 – Lidar classification schema of raw lidar data as delivered following acquisition.

Once the raw topographic and bathymetric sensor data was tiled out, routines were run to reclassify the data into the final classification schema detailed in table 2. This classification schema was used during manual editing and was also the schema used for the final LAS delivered to NOAA as required by the project's SOW.

Lidar Classification – Manual Editing and Final Deliverables	
Class	**Description**
Class 1	Unclassified (includes buildings and vegetation
Class 2	Ground
Class 7	Noise
Class 40	Bathymetric Bottom
Class 41	Water surface
Class 43	Submerged object, not otherwise specified
Class 44	International Hydrographic Organization (IHO S-57 object), not otherwise specified
Class 45	No bathymetric bottom found
Class 46	Bathymetric bottom temporal changes

Table 2 – Final lidar classification schema.

Lidar Acquisition Report

Dewberry elected to subcontract the lidar acquisition and calibration activities to Leading Edge Geomatics. LEG was responsible for providing lidar acquisition, calibration and delivery of lidar data files to Dewberry. The last delivery of data was on September 16, 2019.

LIDAR ACQUISITION DETAILS

LEG planned 992 passes for the project area as a series of parallel flight lines with 44 cross flightlines for quality control. The flight plan included zigzag flight line collection to preempt inertial measurement unit (IMU) drift. In order to reduce potential errors in the data attributable to flight planning, LEG followed FEMA's *Guidelines and Specifications for Flood Hazard Mapping Partners, Appendix A: Guidance for Aerial Mapping and Survey*. The guidances includes the following minimum criteria:

- A digital flight line layout using Leica MissionPro 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;

- Investigation of local restrictions related to air space and any controlled areas so that required permissions can be obtained in a timely manner with respect to project schedule; and
- Filed flight plans as required by local Air Traffic Control (ATC) prior to each mission.

LEG monitored weather and atmospheric conditions and conducted lidar missions only when no conditions existed below the sensor that would affect the collection of data. Good lidar collection conditions include no rain, fog, smoke, mist, or low clouds. LEG also performed in-situ measurements to gauge expected water quality conditions throughout the project area. Lidar systems are active sensors that do not require light. Thus, missions may be conducted during night hours when weather restrictions do not prevent collection. LEG accessed reliable weather sites and indicators (webcams) to establish the highest probability for successful data acquisition.

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

LEG lidar sensors are calibrated at a designated site located at the Lawrence County Airport in Courtland, Alabama and are periodically checked and adjusted to minimize corrections at project sites.

LIDAR SYSTEM PARAMETERS

Leading Edge Geomatics operated a Piper Aztec (Tail # N25FT) outfitted with a RIEGL VQ880-GII Topobathymetric lidar system. Table 3 illustrates Leading Edge Geomatic's system parameters for lidar acquisition on this project.

Item	Bathymetric Sensor Parameter	Topographic Sensor Parameter
Altitude	450 m AGL	450 m AGL
Approx. Flight Speed	130 kts	130 kts
Pulse Rate	200 khz	300 kHz
Scan Rate	80 lps	142 lps
Swath Width	328 m	328 m
Central Wavelength	515 nm	1064 nm
Beam Divergence	0.7 mrad	0.3 mrad
Field of View	40 deg	40 deg
Aggregate Density Achievable	6 ppm	4 ppm
Maximum Num. Returns/Pulse	Up to 10	Up to 10

Table 3 – Leading Edge Geomatic's VQ880-GII Lidar System Parameters

ACQUISITION STATUS REPORT AND FLIGHT LINES

Upon notification to proceed, the flight crew loaded the flight plans and validated the flight parameters. The acquisition manager contacted air traffic control and coordinated flight pattern requirements. Lidar acquisition began immediately upon notification that active control stations were operating. 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 an example of a trajectory from mission 037A flown on February 6th, 2019 with the VQ880-GII using a SmartBase network in Applanix PosPAC.

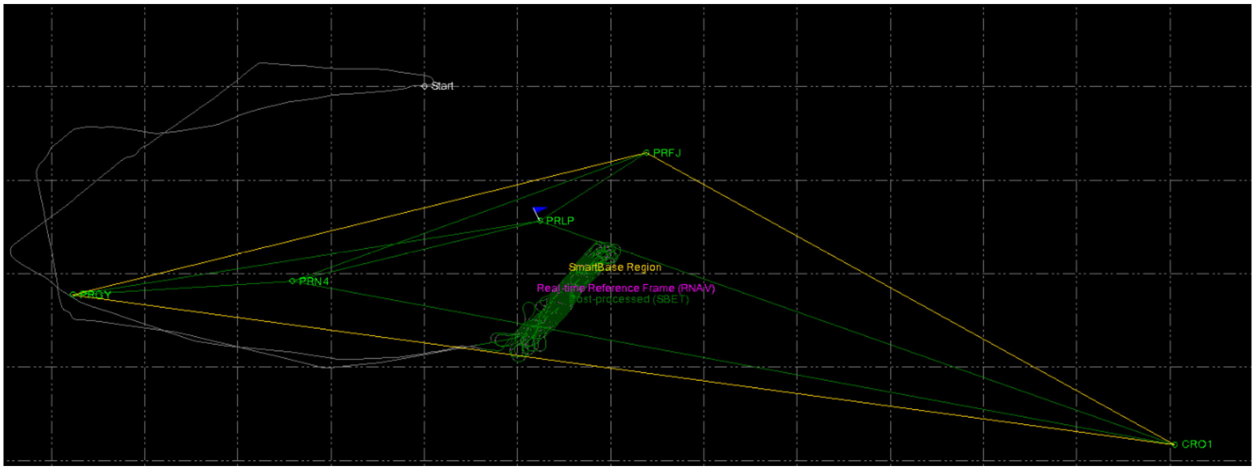

Figure 2 – 037A trajectory as flown by Leading Edge Geomatics

LIDAR CONTROL

Continuously Operating Reference Stations (CORS) were utilized for positioning the majority of data acquired over the course of this project. LEG deployed one static GPS base station toward the end of the acquisition period on the island of St. Thomas to make up for the failure of one CORS base station (VITH). Additionally, position adjustments were calculated for CORS sites CRO1, VITH, and ZSU4 as their published XYZ positions were found to be weak. The coordinates of the utilized base stations are provided in table 4.

Name	NAD83(2011) Lat, Lon		Ellipsoid Ht (NAD83(2011), m)
	Latitude (N)	Longitude (W)	
CORS			
CRO1	17° 45' 24.82134" N	064° 35' 03.55259" W	-30.112
PRAR	18° 27' 01.70483" N	066° 38' 50.72290" W	-18.543
PRFJ	18° 19' 34.73697" N	065° 39' 05.00894" W	-20.768
PRGY	18° 03' 03.41125" N	066° 48' 51.96792" W	35.76
PRHL	18° 22' 48.09108" N	066° 09' 12.81219" W	-22.539
PRJC	18° 20' 32.02394" N	066° 59' 58.19334" W	24.727
PRLP	18° 11' 41.62781" N	065° 52' 05.75074" W	58.883
PRLT	18° 03' 35.40036" N	067° 11' 20.88066" W	-13.36
PRMI	17° 58' 13.41909" N	067° 02' 43.33794" W	-23.594
PRN4	18° 04' 42.91546" N	066° 22' 08.70458" W	131.067
PRAR	18° 27' 01.70483" N	066° 38' 50.72290" W	-18.543
VITH	18° 20' 35.97843" N	064° 58' 09.17171" W	6.283
ZSU4	18° 25' 52.79256" N	065° 59' 36.52039" W	-26.687
LEG			
STB1	8° 21' 31.05330" N	64° 54' 33.85933" W	-10.386

Table 4 – Base stations used to control lidar acquisition for the PR-USVI post-Maria 2019 survey.

AIRBORN GPS KINEMATIC

Airborne GPS data was processed using PosPAC MMS provided by Applanix. Flights were flown with a minimum of 6 satellites in view (13° above the horizon) and with a PDOP of better than 4.

The GPS average residuals for all flights were 3 cm or better, with no residuals greater than 10 cm 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's RiProcess. The data is reviewed for any concerns. Calibration values are determined by RIEGL LMS and reviewed.

Data processing and refraction are performed using a combination of RiProcess and proprietary classification before the lidar is fully exported to LAS format. Data 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. There are also checks performed to determine the quality of bathymetric returns.

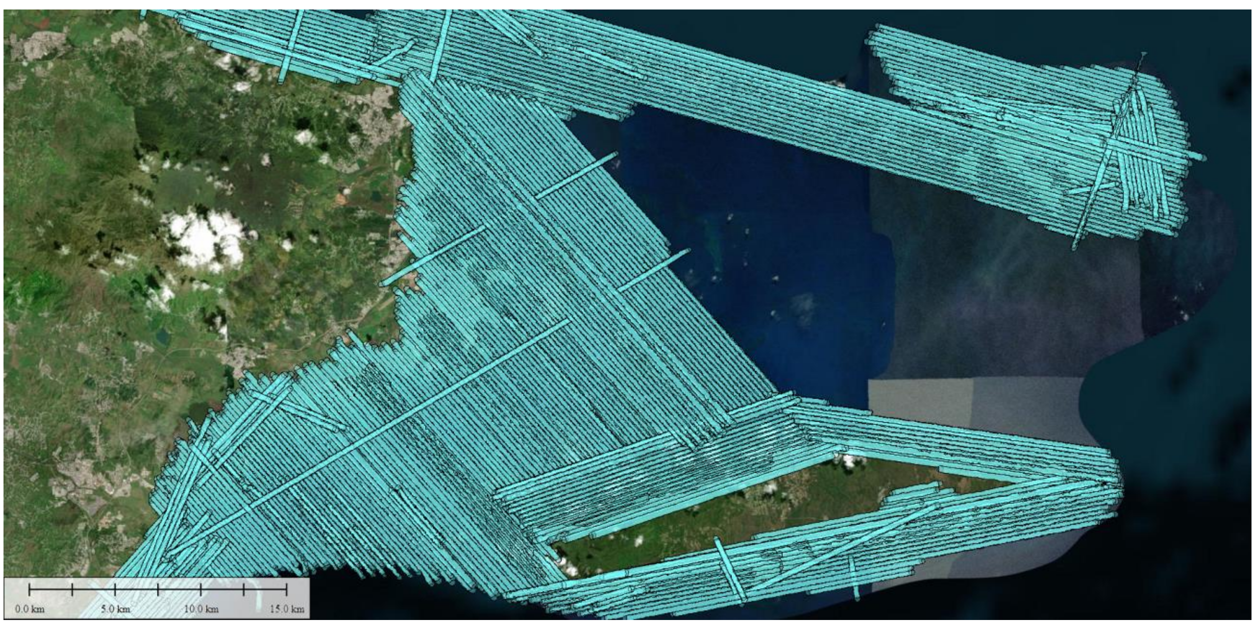

Figure 3 – Sample lidar swath output showing coverage of project area.

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 yaw are optimized during the calibration process until the relative accuracy is met.

Relative accuracy and internal quality are checked using between swaths. 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 follow: relative accuracy ≤ 6 cm maximum differences within individual swaths and ≤ 8 cm $RMSD_z$ between adjacent and overlapping swaths.

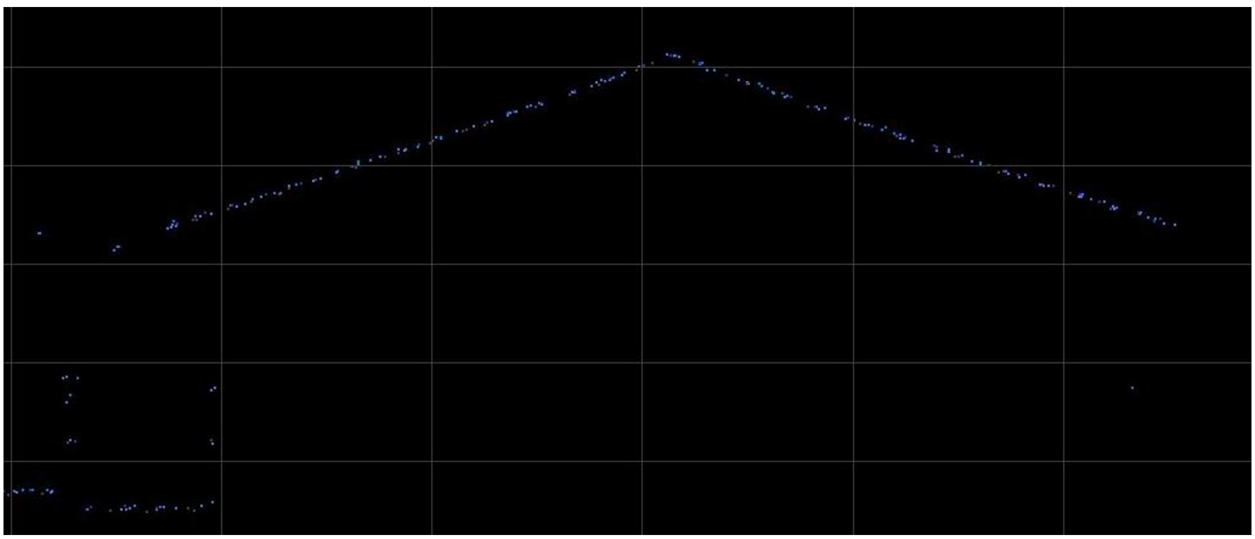

Figure 4 – Profile views showing correct roll and pitch adjustments.

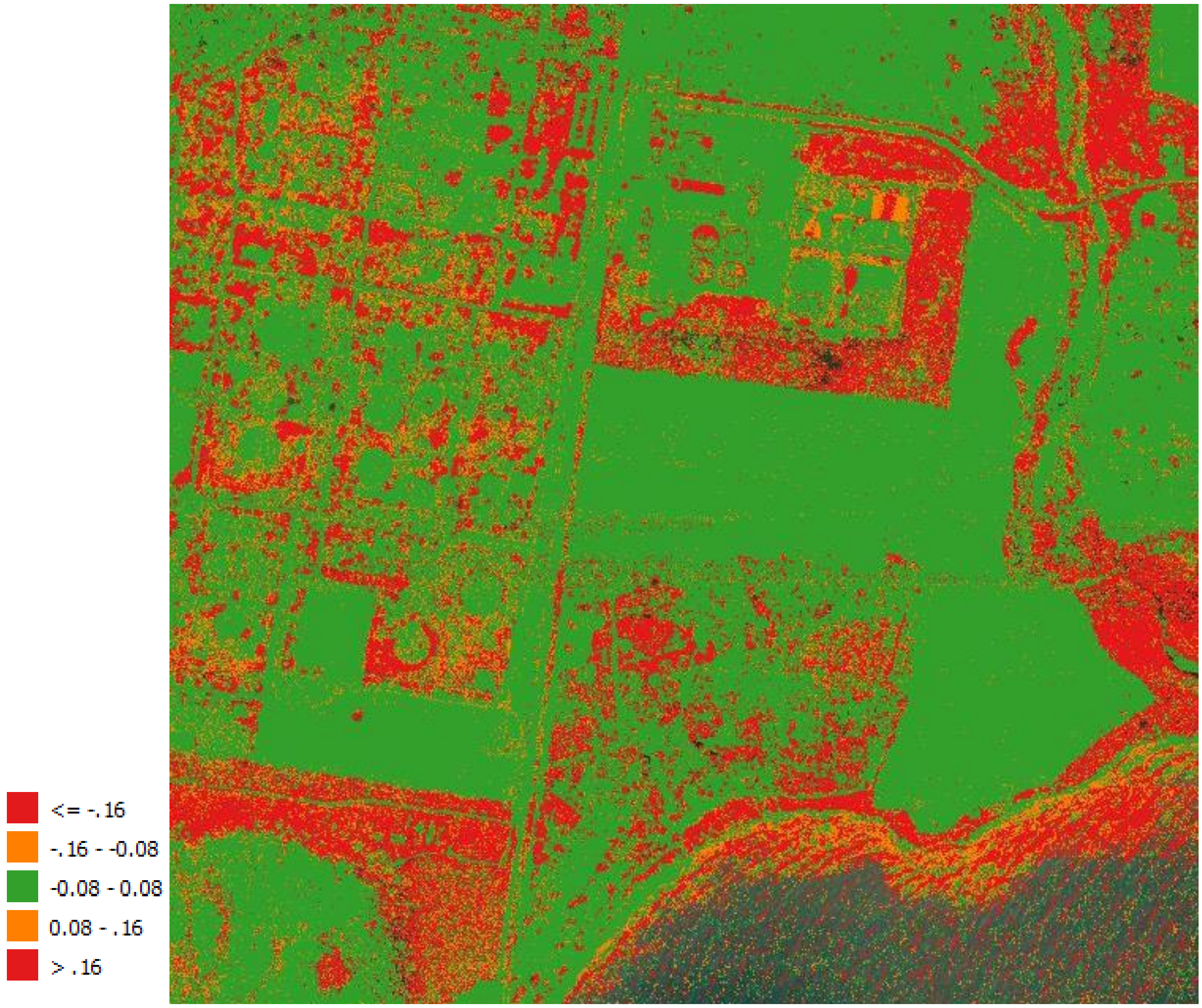

Figure 5 – QC block colored by vertical difference to ensure accuracy at swath edges and throughout.

REFRACTION CORRECTION

Bathymetric data must have a refraction correction applied, which corrects the horizontal and vertical (depth) positions of each data point by accounting for the change in direction and speed of light as it enters and travels through water. The refraction correction was performed by LEG using RiProcess.

PRELIMINARY VERTICAL ACCURACY ASSESSMENT

A preliminary $RMSE_z$ error check is performed by LEG 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 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.

A control bias of -11cm was applied to the dataset as whole. The statistical results with the -11 cm bias applied are provided in table 5.

100 % of Totals	# of Points	RMSEz (m) NVA Spec=0.100 m	NVA at 95% Spec=0.196 m	Mean (m)	Std Dev (m)
Non-Vegetated Terrain	66	0.049	0.097	-0.004	0.049

Table 5 – Static GPS vertical accuracy results.

Overall the calibrated lidar data products collected by LEG meet or exceed the requirements set out in the SOW.

Lidar Processing & Qualitative Assessment

INITIAL PROCESSING

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

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 one hundred and twenty-seven 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 Puerto Rico and US Virgin Islands Topobathemetric Lidar Project satisfies this criteria. This raw lidar swath data set was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 10 cm $RMSE_z$ Vertical Accuracy Class. Actual NVA accuracy was found to be $RMSE_z$ = 7.7 cm, equating to +/- 15.0 cm at 95% confidence level. The table below shows all calculated statistics for the raw swath data.

100 % of Totals	# of Points	RMSEz (m) NVA Spec=0.100 m	NVA- Non-vegetated Vertical Accuracy ((RMSEz x 1.9600) Spec=0.196 m	Mean (m)	Median (m)	Skew	Std Dev (m)	Min (m)	Max (m)	Kurtosis
NVA	127	0.077	0.150	-0.036	-0.042	-0.052	0.068	-0.284	0.141	0.519

Table 6 – NVA at 95% confidence level for raw swaths.

Inter-Swath (Between Swath) Relative Accuracy

Dewberry verifies inter-swath or between swath relative accuracy of the dataset by creating Delta-Z (DZ) orthos. According to the SOW and ASPRS Positional Accuracy Standards for Digital Geospatial Data, 10 cm Vertical Accuracy Class or QL2 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. Bathymetric areas may be yellow or red due to varying elevations of returns within the water column. Large or continuous sections of yellow or red pixels following flight line patterns and not the terrain, vegetation, or bathymetric areas can indicate the data was not calibrated correctly or that there were issues during acquisition that could affect the usability of the data. The DZ orthos for Puerto Rico and US Virgin Islands Topobathemetric Lidar Project are shown in the figure below; this project meets inter-swath relative accuracy specifications.

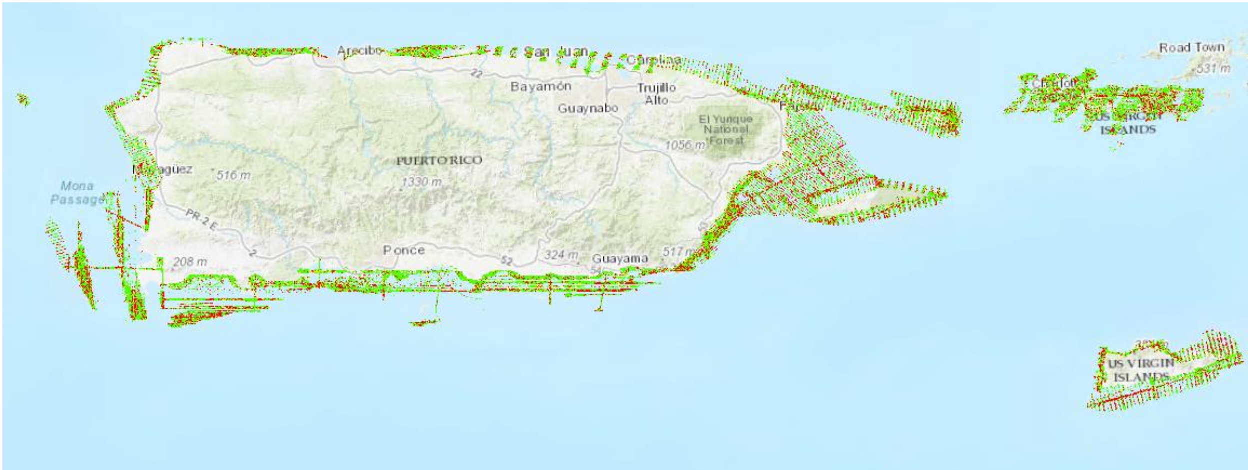

Figure 6 – DZ orthoimages. Offsets between flight lines of 0-8 cm are green, 8-16 cm are yellow, and above 16 cm are red. Larger offsets in vegetated and bathymetric areas are expected as different returns from water column and vegetation can occur between different flight lines. Inter-swath relative accuracy passes specifications.

Intra-Swath (Within Swath) Relative Accuracy

Dewberry verifies the intra-swath (within swath) relative accuracy by using Esri and GeoCue software to generate Z-range rasters that colorize the precision of the laser point density within each swath. Visual inspections are performed using these z-range rasters. Areas that are not aligned with project specifications are flagged and investigated. According to the SOW and ASPRS Positional Accuracy Standards for Digital Geospatial Data, 10 cm Vertical Accuracy Class or QL2 data must meet intra-swath relative accuracy of 6 cm maximum difference or less.

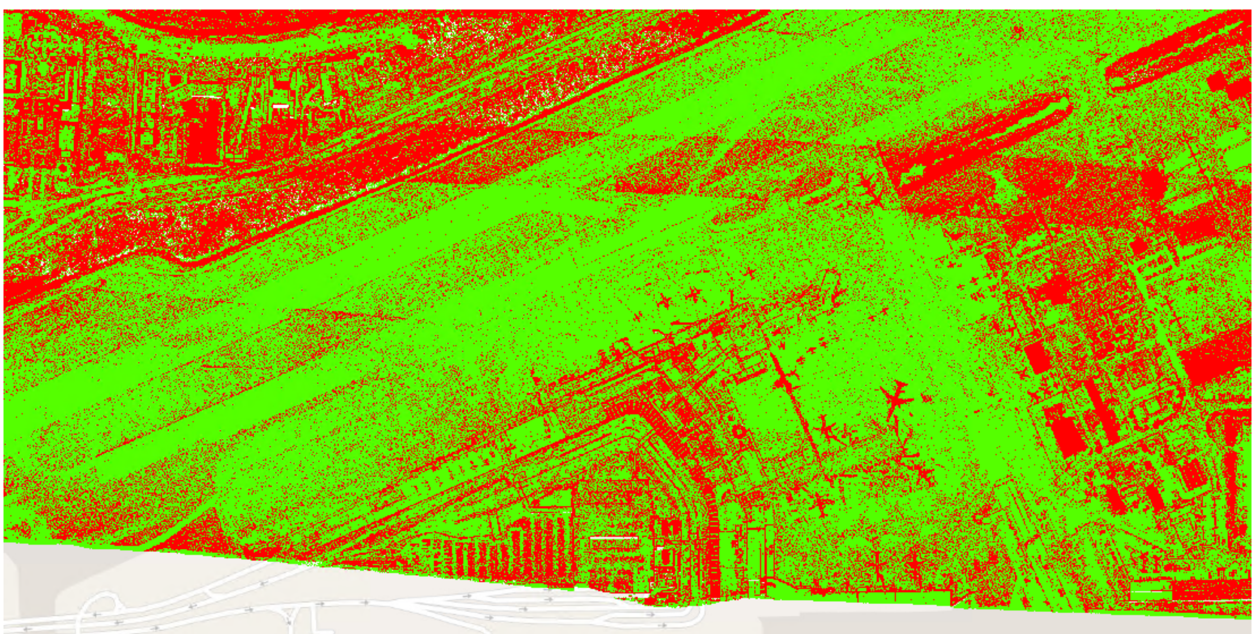

Figure 7 – Intra-swath relative accuracy. Areas where the maximum difference is ≤6 cm per pixel within each swath are colored green and areas exceeding 6 cm are colored red. Flat, open areas like this runway are the most reliable metric of intra-swath relative accuracy. Intra-swath relative accuracy passes specifications for this project.

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 Puerto Rico and US Virgin Islands Topobathemetric Lidar Project; no horizontal alignment issues were identified.

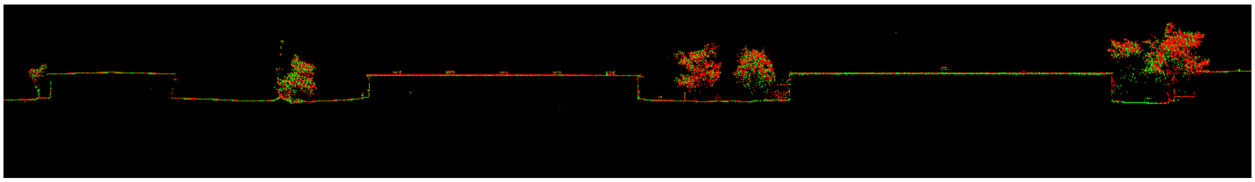

Figure 8 – Two separate flight lines differentiated by color (Green/Red) are shown in this profile. There is no visible horizontal offset between these two flight lines.

Point Density and Spatial Distribution

For topographic areas, the required Nominal Point Spacing (NPS) for this project is no greater than 0.71 meters, which equates to a Nominal Point Density (NPD) of 2 points per square meter (ppsm) or greater. For bathymetric areas, the required Nominal Point Spacing (NPS) for this project is no greater than 1.41 meters, which equates to a Nominal Point Density (NPD) of 0.5 ppsm or greater.

Density calculations were performed using first return data only located in the geometrically usable center portion (typically ~90%) of each swath. The project area was determined to have a combined NPS of 0.48 meters or an NPD of 4.28 ppsm which satisfies the project requirements. A visual review of a 1-square meter density grid (figure 9) shows that there are some 1-meter cells that do not contain 2 ppsm (red areas) due to the irregular spacing of lidar point cloud data and the inclusion of bathymetric areas in the 2 ppsm count (bathymetric areas are considered passing if they have 0.5 ppsm). Most cells contain at least 2 ppsm (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.

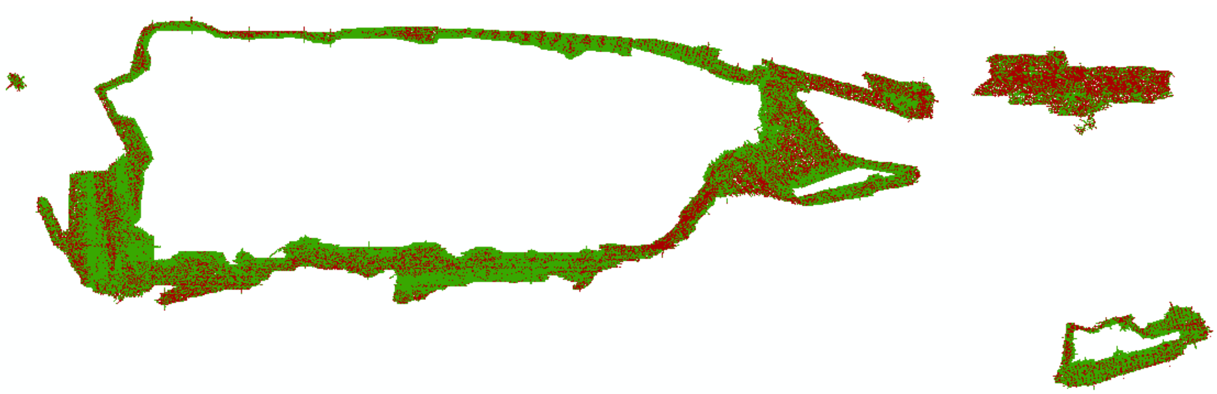

Figure 9 – 1-square meter density grid. There are some 1-meter cells that do not contain 2 ppsm (red areas) due to the irregular spacing of lidar point cloud data and inclusion of bathymetric areas in this more stringent threshold. Most 1-sqaure meter cells contain at least 2 points per square meter (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 a cell size equal to the design NPS*2. ArcGIS tools are then used to calculate the number of first return points within each grid cell. At least 90% of the cells must contain 1 lidar point, excluding acceptable void areas such as low NIR reflectivity features, i.e. some asphalt and roof composition materials. This project passes spatial distribution requirements, as shown in the figure 10.

Figure 10 – All cells (2*NPS cellsize) containing at least one lidar point are colored green. Cells that do not contain a lidar point are colored red. 98.7% 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. Data processing included breakline creation to define the land/water interface, automated and manual editing of the lidar tiles, QA/QC, and final formatting of the LAS files.

Breakline Creation and QA/QC

Refraction extents representing the boundary between refracted (bathymetric) and nonrefracted (topographic) points must be created so that bathymetric bottom and ground points can be classified properly in the lidar. The processing software for the Rigel 880 GII system does a basic classification on the lidar, differentiating between land and bathymetric areas. The points designated as bathymetry are then refracted. These refracted points are aggregated into polygons using LAStools and ArcGIS. As the refraction extents are created from the lidar data, they inherit the horizontal accuracy of the source lidar.

The refraction extent delineation is used to finalize the lidar classification of ground and bathymetric points (figure 11).

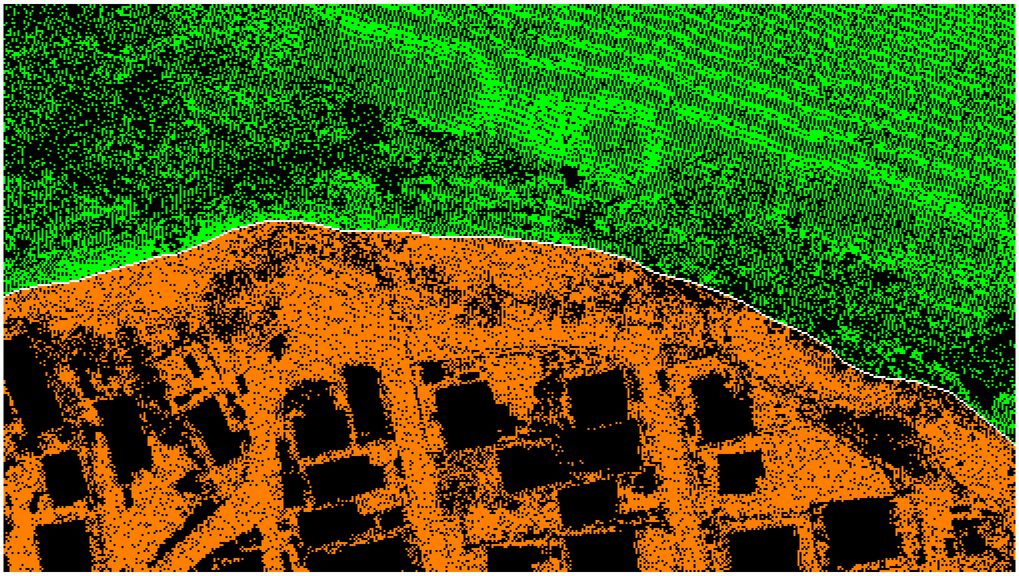

Figure 11 – Tile 2019_833300e_2041500n_las. The refraction extent is shown as a white line. The lidar point cloud shows topographic points in orange and bathymetric points in green.

GeoCue and Terrascan Processing

Next 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 to create the initial automated ground and bathy bottom classifications, using the final project classification schema.

This routine classifies any obvious low outliers in the dataset to class 7. 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.

The final breaklines defining the land/water interface are then used to classify “ground” points within the water breaklines as bathymetric bottom. The breaklines are also used as part of the classification routines to ensure water surface and water column points are classified correctly.

Each tile was then imported into Terrascan and a surface model was created to examine the ground (class 2) and bathy bottom (class 40) classification. 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 and that class 40 accurately represents submerged topography. Dewberry analysts visually reviewed the surface models and corrected errors in the ground classification such as vegetation, buildings, and bridges that were present following the initial processing conducted by Dewberry. Common errors in the bathymetric classification that were corrected by Dewberry include some of the issues outlined below.

Special attention was given along shorelines or the land/water interface as no hard edges or seams should exist between ground and bathy bottom.

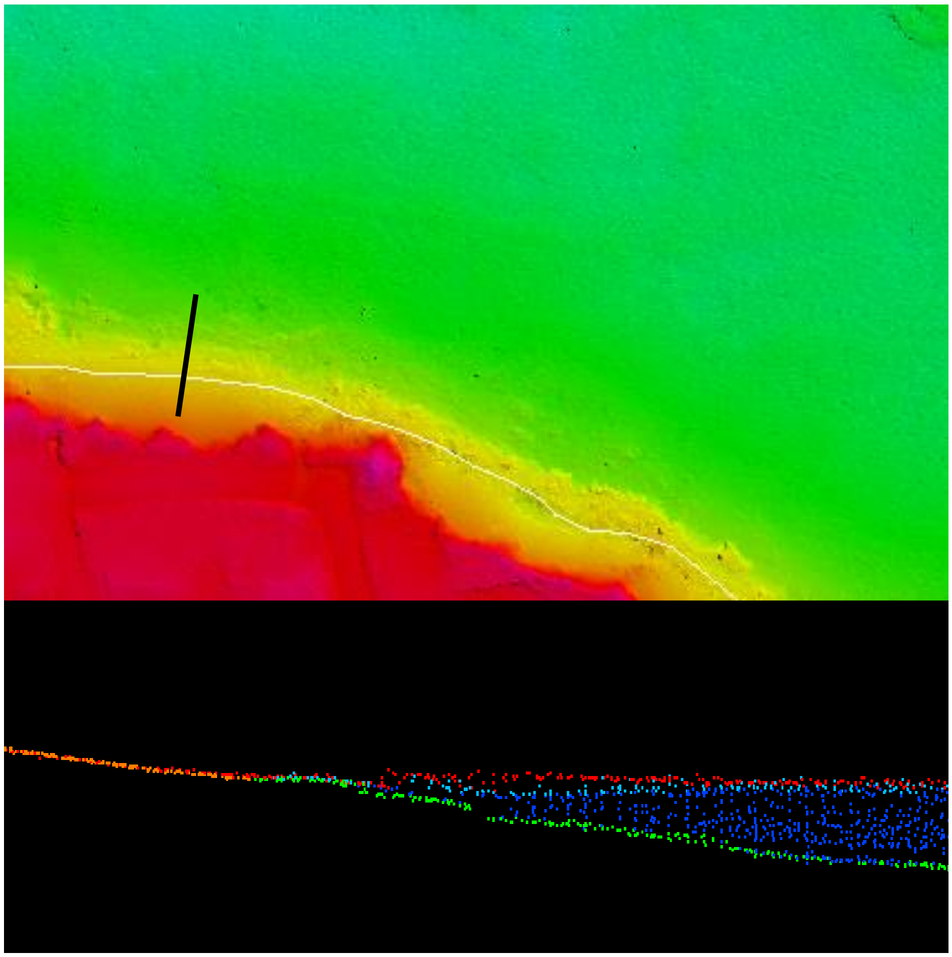

Figure 12 – The land water interface should be seamless with no hard edges or seamlines. The topobathy surface model is shown on the top with a profile location overlaid. The profile is shown in the image below where bathy bottom points are green, water surface points are turquoise, and water column points are blue, ground points are orange, and unclassified points are red.

Areas of rapids or swift moving water may also need to be removed from the bathy bottom class as these may be surface or water column points and not bathy bottom points due to the water movement and stirring of sediment (increased turbidity). When possible, color orthos were used to help determine water clarity and likelihood of full penetration to the submerged bottom. Generally, editors looked for consistency in data, especially continuous topography (connecting the dots method to ensure channel geometry is reasonable).

Special attention was given in deeper areas where there may not be any true bathy bottom points, but the automated algorithm classified lower water column points as bathy bottom.

When evaluating points to determine if they are low water column points or true bathy bottom, the following rules were used as guidelines to maintain accuracy and consistency:

1. Gradient consistency – if the points are part of consistent gradients or consistent channel geometry, they are more likely to be bathy bottom rather than low water column noise. Conversely, points that would cause abrupt changes or inconsistency in the overall gradient or channel geometry are less likely to be bathy bottom points, especially if the abrupt change would result in shallower (higher) bathy bottom points above lower bathy bottom points with a high confidence.

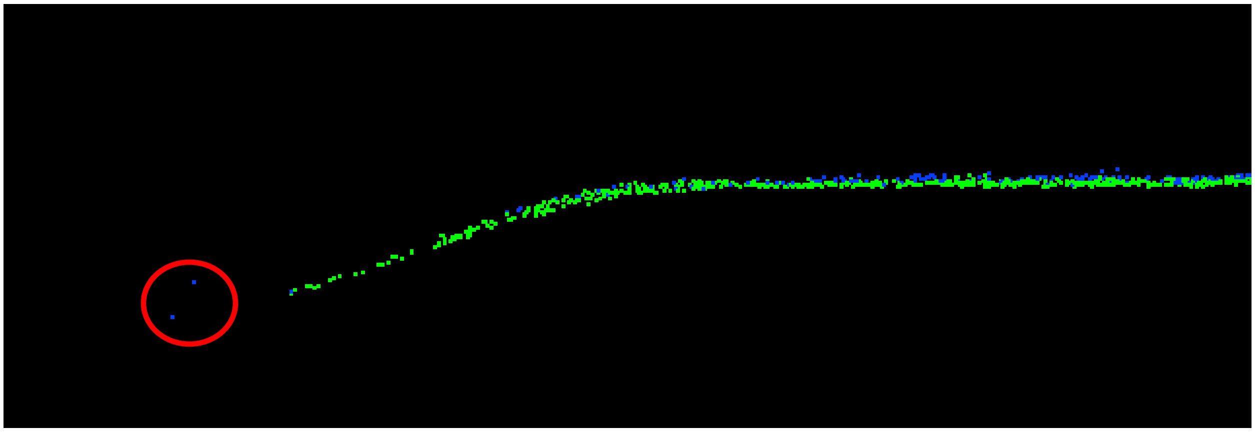

Figure 13 – Bathy bottom points (green) are shown with water column (blue) and water surface points (turquoise) in this profile. The two water column points circled in red would cause inconsistent and upward changes in the topobathy model if these points were classified to bathy bottom. These points should remain classified as water column.

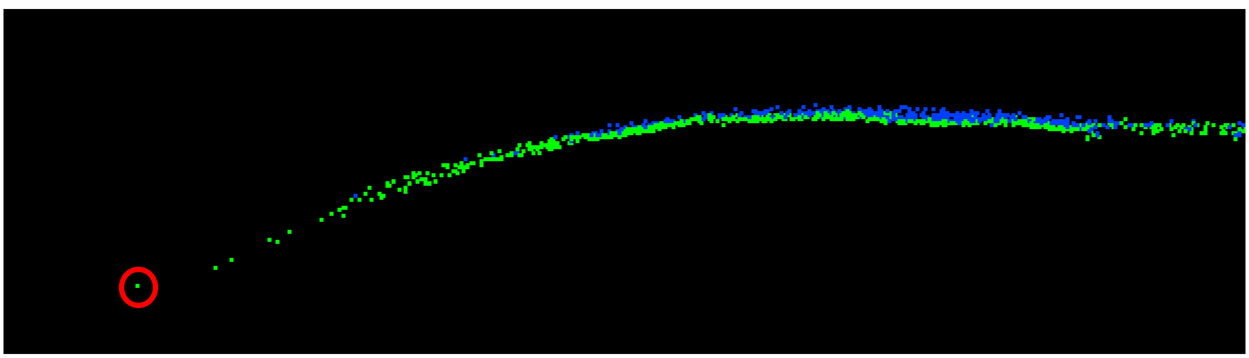

Figure 14 – Bathy bottom points (green) are shown with water column (blue) and water surface points (turquoise) in this profile. The bathy bottom point circled in red is isolated, but maintains a consistent gradient with other bathy bottom points to the east. This point should remain classified as bathy bottom.

2. Small gap verification – if bathy bottom was obtained for the vast majority of a channel, but small random gaps or voids in the bathy bottom exist after the initial grounding where it is unclear if existing points are bathy bottom or low water column, these small gaps should usually be filled by classifying the points in question to bathy bottom. It is unlikely such small portions of the channel are that much deeper where no bathy bottom was obtained when the lidar penetrated to the bathy bottom in the rest of the channel. However, if the gaps/voids are larger or consistently form over specific areas or locations, then these areas are more likely to represent deeper areas where the lidar may

not have penetrated to the submerged bottom. In these areas, points should be classified as no bottom found.

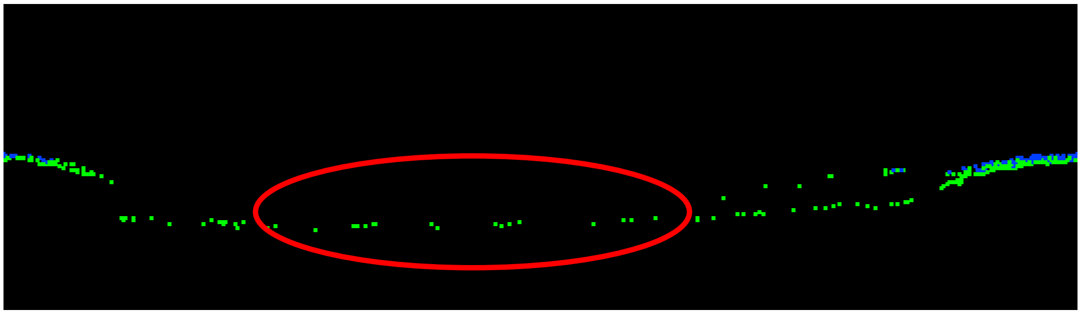

Figure 15 – Bathy bottom points (green) are shown with no bottom found (blue) and water surface points (turquoise) in this profile. The bathy bottom points circled in blue were classified as bathy noise by the initial grounding macro, resulting in a small void. These points were re-classified as bathy bottom to the fill the small gap because they are at the same depth as surrounding points, maintain a consistent gradient, and are more likely to be submerged bottom rather than low water column noise.

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.

Submerged Objects

When objects were encountered that were blatantly foreign to the natural bathymetric surface, these features were considered submerged objects and classified as class 43-submerged object or class 44 – International Hydrographic Organization (IHO) S-57 Object.

Temporal Changes

Data acquisition for the project area was collected over a wide time period (January-June 2019 2018 thru May 2019). Due to varying environmental conditions at the time of different acquisitions, there may be temporal changes within and between flightlines where missions from different acquisitions are merged together. Areas of temporal changes were identified during the manual editing and review of the lidar data. An additional classification, class 46 – temporal, was added to the final classification schema to accommodate these temporal differences within the data. Class 46 was used when data was edited to classify out the incorrect ground/bathy surface (to class 46), and classify in the correct ground/bathy surface from class 1/45 (e.g., figure 16)

When temporal changes were discovered in the dataset, the following priorities were maintained:

1. Use most recent flight lines to model bathy bottom data.
2. Use older flight lines if it will provide full coverage, will prevent ridges/abrupt changes in the data, or represents better water clarity (i.e. bathy returns) than more recent data.
3. If ridge/abrupt change is unavoidable or boundaries for #1 or #2 are not definable, then use more recent data to full extent and fill in with older/earlier collect where necessary.

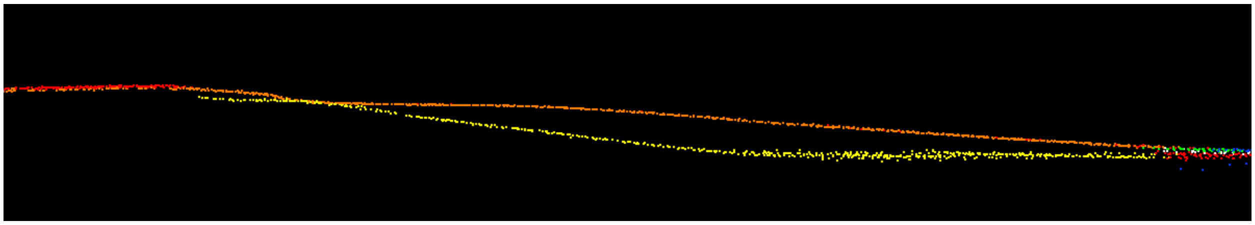

Figure 16 – Points colored by class showing the elevation differences along the identified ground surface. Orange represents ground, yellow represents the temporal class (i.e. less-recent ground), green represents bathymetry, blue is no bottom found, and red is unclassified. Care was taken to use the most recent data to represent the topobathy surface. In this example, the orange line represents the most current ground while yellow represents a ground surface captured from different day's flight; the green bathymetric surface was not affected in this example.

Flightline Ridge

The flat geographic characteristics of the AOI along the eastern coastline of Puerto Rico offered unique challenges post-acquisition during flightline calibration. Flightline ridges occasionally appear in the final digital elevation model in the flat bathymetric surfaces in back bay areas. Every attempt was made to eliminate or minimize these data artifacts. Although these ridges are fully within the projects specifications (≤ 10 cm), they are visible in the final digital elevation model. Figure 17 illustrates an example of one of these data artifacts.

Figure 17 – Flightline ridges similar to the one circled in red occasionally appear in deep bathymetric areas throughout the AOI. Although every attempt was made to eliminate or minimize these data artifacts, some still appear in the final digital elevation model.

Since different software and different view settings are used to view geospatial data, these flightline ridges may appear more or less pronounced to different users.

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 topobathymetric Digital Elevation Model (DEM). This includes creating pseudo image products such as lidar orthos produced from the intensity returns, Triangular Irregular Network (TIN)'s, Digital Elevation Models (DEM), void polygons and 3-dimensional models as well as reviewing the actual point cloud data.

Visual Review

During QA/QC, reviewers check for consistent and correct classification. 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, areas where bathymetry was not classified correctly to produce an accurate submerged topography model, and other classification errors. Reviewers verified all guidelines outlined in the Data Classification and Editing section above have been adhered too.

Create Void Polygons

Void polygons were created as part of QA/QC. The void polygons identify areas of sparse to no bathymetric bottom points. The void polygons were loaded when reviewing the data to ensure correct and full classification of bathy bottom. All void areas 9 sq m or larger in the bathymetry domain were delineated with a void polygon.

The void polygon layer was generated using LAStools and ArcGIS to eliminate interpolation across areas greater than 9 square meters in the bathy class (40) for the final elevation raster. A DEM was created using LAStools' 'las2dem' utility, which created and rasterized a TIN from the LAS data. A user-defined threshold specifying the maximum allowable edge length during triangulation was set to 4 m, restricting rasterization in areas of sparse data. Once the constrained DEM was created, ArcGIS was used to vectorize the void (NoData) areas. The resulting polygons were then used to constrain interpolation in the final elevation raster.

Formatting

After the final QA/QC is performed and all corrections have been applied to the dataset, all lidar files are updated to the final format requirements and the final formatting, header information, point data records, and variable length records are verified using Dewberry proprietary tools. Table 7 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 19/20, meters and Ellipsoid, meters in WKT Format	Pass
Global Encoder Bit	17	Pass
Time Stamp	Adjusted GPS Time (unique timestamps)	Pass

Classified Lidar Formatting		
Parameter	**Requirement**	**Pass/Fail**
System ID	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	Class 0: Created, Never Classified Class 1: Unclassified Class 2: Ground Class 7: Noise Class 40: Bathymetric Bottom (submerged topography) Class 41: Water Surface Class 43: Submerged Object, not otherwise specified Class 44: International Hydrographic Organization (IHO) S-57 Object, not otherwise specified Class 45: No Bathymetric Bottom Found Class 46: Temporal Surface	Pass
Overlap and Withheld Points	Points trimmed from overlap edges are flagged as withheld	Pass
Scan Angle	Recorded for each pulse	Pass
XYZ Coordinates	Unique Easting, Northing, and Elevation coordinates are recorded for each pulse	Pass

Table 7 – LAS formatting of final deliverables.

Derivative Lidar Products

STANDARD DEVIATION

Per the project SOW, a confidence layer that reports the standard deviation of all ground and submerged topography points within each 1 meter grid cell has been created for the entire project area. Each 1 meter grid cell has an associated standard deviation value, in meters. The confidence layer extents are the same as the extents for the final topobathymetric DEMs so that the pixels align, showing the confidence of each topobathymetric DEM grid cell. The confidence layer shows the standard deviations of topobathymetric points on a cell-by-cell basis. However, changing the symbology of the confidence layer will allow ranges or bins to be set so that the layer can be grouped by threshold and analyzed over large areas.

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 sixty two (262) check points were surveyed for the project and are located within bare earth, vegetated, and submerged topography 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. Figure 24 shows the location of the QA/QC checkpoints used to test the positional accuracy of the dataset.

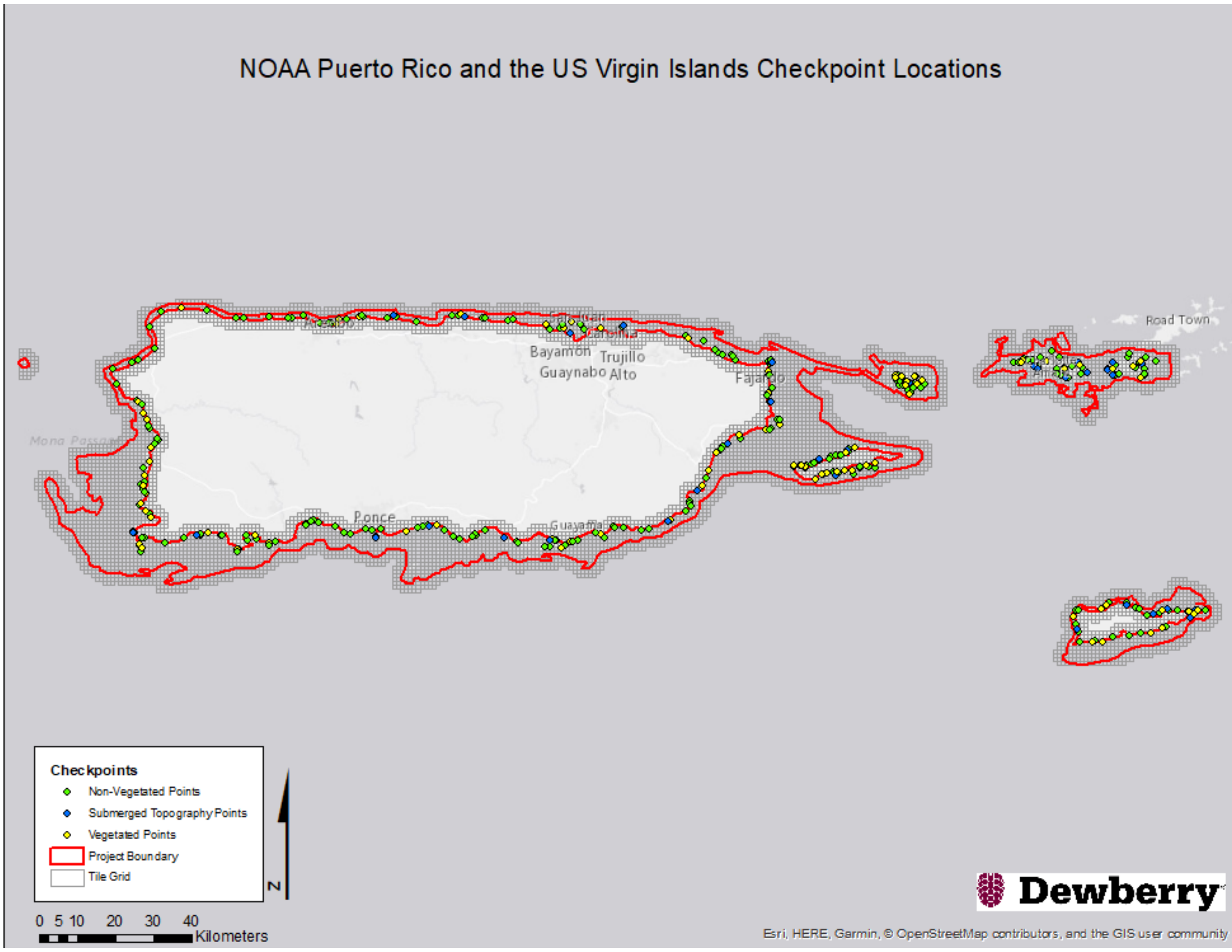

Figure 18 – Location of QA/QC checkpoints.

All checkpoints surveyed for vertical and horizontal accuracy testing purposes are listed in table 8.

Point ID	NAD83 (2011) UTM Zone 19 and 20		NAD83(2011) epoch:2010
	Easting X (m)	Northing Y (m)	Elevation (m)
NVA-002	706774.066	1988334.025	-39.486
NVA-003	716945.993	1984777.462	-29.782
NVA-005	736338.867	1992530.277	-37.316
NVA-010	691715.308	2000403.594	-28.800
NVA-024	684908.817	2028032.286	-38.368
NVA-030	740997.087	2044045.243	-33.860
NVA-031	755739.763	2045460.463	-40.921
NVA-057	773055.779	1988133.857	-35.417
NVA-059	752772.431	1987981.688	-37.123
NVA-060	744545.622	1989029.400	-33.462

Point ID	NAD83 (2011) UTM Zone 19 and 20		NAD83(2011) epoch:2010
	Easting X (m)	Northing Y (m)	Elevation (m)
NVA-061	805734.603	1987011.931	-29.448
NVA-062	815214.727	1990782.140	-36.093
NVA-064	835050.415	1997305.691	-20.288
NVA-074	843628.067	2011604.249	-38.921
NVA-085	856081.120	2033263.036	37.868
NVA-091	869189.150	2008155.305	-38.081
NVA-092	870169.554	2004346.349	-12.894
NVA-093	872674.149	2004916.606	-20.170
NVA-094	876613.580	2010349.553	-27.796
NVA-096	892518.175	2026268.415	-21.725
NVA-097	890820.994	2028602.441	-38.964
NVA-098	893811.314	2027618.149	-38.502
NVA-099	285838.262	2030376.866	96.191
NVA-100	288422.816	2031363.113	70.997
NVA-101	290828.902	2030752.280	230.496
NVA-102	292101.704	2028941.525	-37.392
NVA-105	297692.319	2031164.074	16.591
NVA-106	297134.151	2028132.317	-39.350
NVA-107	299846.932	2025970.055	-38.690
NVA-108	299163.512	2028694.498	31.083
NVA-110	303665.224	2028547.930	-35.509
NVA-111	303279.630	2026716.977	-9.963
NVA-113	312245.563	2026235.603	-0.049
NVA-114	312522.680	2028849.205	173.120
NVA-116	317657.342	2027785.680	285.714
NVA-118	319939.320	2025692.647	55.045
NVA-119	319841.061	2027422.130	-35.030
NVA-121	315761.036	2030728.738	-40.475
NVA-122	320307.625	2030394.404	-40.247
NVA-123	323121.615	2029492.354	-12.481
NVA-125	299968.092	1961174.461	-40.698
NVA-126	299964.535	1964840.647	-39.013
NVA-131	309272.281	1957583.491	-38.041
NVA-139	315775.936	1965174.214	-30.846
NVA-143	322069.231	1963635.282	-39.816
NVA-144	326606.330	1964222.034	-24.347
NVA-145	329354.225	1963756.238	-38.079
NVA-202	892993.923	2025730.666	-7.492
NVA-203	889431.554	2028950.135	-35.113
NVA-206	896576.958	2028196.932	-39.603

Point ID	NAD83 (2011) UTM Zone 19 and 20		NAD83(2011) epoch:2010
	Easting X (m)	Northing Y (m)	Elevation (m)
NVA-209	895574.307	2026915.419	18.440
NVA-214	766350.539	1991099.513	-38.467
NVA-217	824347.621	1989985.873	-36.307
NVA-222	865747.332	2006682.032	-37.106
NVA-224	872228.166	2009111.231	-33.423
NVA-226	693546.478	2042948.093	-27.725
NVA-228	693577.519	1994141.135	-34.993
NVA-232	803718.710	2041443.064	-40.998
NVA-234	815484.913	1990520.622	-37.369
NVA-235	789688.245	1986756.450	-38.467
NVA-237	721635.379	1987565.715	-38.926
NVA-238	883655.148	2005904.024	-33.677
NVA-245	847217.875	2034440.158	-37.029
NVA-252	856540.031	2016263.387	-24.006
NVA-264	842978.346	2010639.018	-38.661
NVA-265	856670.711	2027007.917	-36.085
NVA-269	801076.263	2042768.641	-40.820
NVA-271	779158.257	1988563.993	-37.427
NVA-279	874149.650	2004674.800	-38.521
NVA-284	780876.929	2045403.669	-41.447
NVA-290	798554.606	1985507.564	-37.991
NVA-292	692223.585	1987725.188	-36.508
NVA-307	866984.532	2007089.529	-32.086
NVA-312	855710.796	2034134.850	-37.865
NVA-315	690824.741	1996534.835	-38.327
NVA-323	855639.133	2025313.039	-36.355
NVA-328	719304.542	1987097.575	-39.560
NVA-334	724678.788	2045540.300	-32.221
NVA-339	800236.845	1987090.919	-36.215
NVA-356	691133.369	2001617.695	-35.364
NVA-359	691923.797	2005985.190	-39.366
NVA-364	694794.300	2012250.653	-38.683
NVA-365	693361.044	2016474.361	-37.454
NVA-371	688861.915	2033572.673	-41.599
NVA-379	878149.079	2004472.222	-26.004
NVA-382	894421.984	2030110.533	46.346
NVA-383	889819.457	2030260.744	-38.690
NVA-391	863954.560	2006563.613	-40.378
NVA-394	862539.455	2006311.915	-40.709
NVA-509	774501.903	2046133.101	-42.092

Point ID	NAD83 (2011) UTM Zone 19 and 20		NAD83(2011) epoch:2010
	Easting X (m)	Northing Y (m)	Elevation (m)
NVA-511	833980.911	2040538.597	-40.681
NVA-512	858425.353	2018746.508	-38.158
NVA-513	835239.655	1996830.532	-2.195
NVA-514	802529.280	1985723.468	-38.215
NVA-515	770934.626	1989838.914	-38.449
NVA-516	750039.935	1990099.827	-38.226
NVA-517	690991.155	1985873.884	-39.821
NVA-518	689593.923	1989037.895	-29.912
NVA-519	695771.760	2013539.412	-38.702
NVA-520	690152.899	2023623.037	-40.107
NVA-522	708380.964	2047397.878	-32.558
NVA-523	730666.323	2045515.213	-26.519
NVA-524	749410.053	2045766.659	-38.339
NVA-525	787564.589	2044619.813	-41.401
NVA-526	806290.030	2043842.481	-41.716
NVA-527	842584.301	2036240.707	-40.101
NVA-528	726437.509	1986898.522	-16.473
NVA-529	702637.515	1987740.910	-39.179
NVA-530	697650.304	1986321.549	-33.373
NVA-600	316736.866	1958532.655	-30.845
NVA-601	316524.305	1964663.314	-40.024
NVA-602	300659.292	1956564.361	-38.389
NVA-603	313314.039	2026545.612	-8.561
NVA-604	297965.711	2026499.958	-35.877
NVA-605	292857.208	2031483.718	67.856
NVA-606	893698.473	2028085.861	-40.737
NVA-607	890154.869	2027675.095	-40.174
NVA-608	879746.704	2005951.704	-39.324
NVA-609	873397.893	2009408.581	-31.438
NVA-610	845932.974	2035740.324	-40.468
NVA-611	807434.143	2042515.433	-40.249
NVA-612	763494.031	2044418.105	-40.421
NVA-613	718297.941	2045267.225	12.581
NVA-614	690557.529	2034460.812	-38.815
NVA-615	692268.214	2002555.582	-39.699
NVA-616	691235.177	1984192.905	-39.619
NVA-617	754243.028	1989968.648	-35.698
NVA-618	781611.967	1989780.120	-35.447
NVA-619	817601.873	1990496.123	-32.834
NVA-620	833938.679	1994673.825	-33.864

Point ID	NAD83 (2011) UTM Zone 19 and 20		NAD83(2011) epoch:2010
	Easting X (m)	Northing Y (m)	Elevation (m)
NVA-621	848392.173	2013735.447	-38.959
NVA-622	857927.209	2018841.693	-37.696
PID-111	324301.000	1964258.609	-38.027
PID-116	333841.713	1963877.194	26.567
PID-117	323420.542	1959817.889	-34.742
PID-120	318459.719	1963110.397	-36.401
PID-122	300362.102	1959342.877	-39.039
PID-127	291334.868	2029092.983	-19.985
PID-133	301043.660	2028847.817	73.980
PID-430	843390.242	2010966.075	-38.332
PID-434	858672.890	2018829.497	-38.276
PID-435	745140.501	2045172.530	-37.717
PID-440	867837.375	2007361.903	-28.338
PID-444	841857.583	2037083.757	-39.663
PID-454	822550.520	1989863.455	-30.419
PID-455	839467.074	2003265.577	-37.717
PID-459	691672.138	1987570.400	-37.014
PID-462	741987.481	1990620.141	-35.257
PID-467	835387.541	1996206.248	-35.179
PID-469	889616.085	2030416.367	-39.740
PID-490	879684.045	2006363.437	-35.925
PID-491	789999.961	1986498.555	-38.620
PID-501	855985.629	2015915.570	-37.430
PID-502	716307.489	2045501.115	0.601
PID-505	812819.801	1987815.440	-38.314
PID-506	716569.139	1984057.994	-30.435
PID-507	733856.616	2045865.518	-41.631
ST-101	292151.235	2028491.772	-42.832
ST-103	299478.887	2025768.841	-42.504
ST-106	310230.153	2027342.548	-42.807
ST-107	319459.483	2028999.241	-42.618
ST-108	311761.195	2029462.767	-42.591
ST-109	311508.742	2026173.875	-42.756
ST-310	766647.072	1990844.419	-40.197
ST-322	705988.681	1988345.170	-40.476
ST-373	876422.334	2010721.879	-42.106
ST-400	803738.433	2041524.114	-43.362
ST-401	817931.643	2043486.657	-43.846
ST-402	856747.714	2033680.341	-42.586
ST-405	856375.827	2023341.105	-42.054

Point ID	NAD83 (2011) UTM Zone 19 and 20		NAD83(2011) epoch:2010
	Easting X (m)	Northing Y (m)	Elevation (m)
ST-408	844996.792	2012537.541	-40.622
ST-410	837019.997	2000074.155	-41.271
ST-411	829493.105	1991999.490	-41.182
ST-415	798400.567	1987055.747	-40.233
ST-416	786507.320	1987714.219	-40.267
ST-419	752914.524	1987806.816	-40.301
ST-420	689077.574	1989027.674	-40.871
ST-423	757404.634	2045954.130	-44.670
ST-424	776207.984	2045847.288	-44.332
ST-425	873389.090	2004218.934	-42.602
ST-426	891561.781	2028392.173	-42.621
ST-408	844996.792	2012537.541	-40.622
ST-410	837019.997	2000074.155	-41.271
ST-411	829493.105	1991999.490	-41.182
ST-415	798400.567	1987055.747	-40.233
ST-416	786507.320	1987714.219	-40.267
ST-419	752914.524	1987806.816	-40.301
ST-420	689077.574	1989027.674	-40.871
ST-423	757404.634	2045954.130	-44.670
ST-424	776207.984	2045847.288	-44.332
ST-425	873389.090	2004218.934	-42.602
ST-426	891561.781	2028392.173	-42.621
ST-427	892770.964	2028259.996	-42.587
ST-428	869137.491	2008310.363	-41.954
ST-74	320194.824	1963364.141	-41.961
ST-77	323973.615	1964378.074	-41.830
ST-80	331165.309	1963923.196	-41.945
ST-82	329690.129	1962145.177	-41.799
ST-85	300197.515	1959941.751	-41.868
ST-88	313397.506	1965901.787	-42.245
ST-89	304915.333	2026965.151	-43.000
ST-91	302841.054	2029798.468	-42.738
ST-97	291068.767	2029290.991	-42.983
VVA-001	890887.715	2030171.255	91.151
VVA-002	894845.861	2028011.714	14.807
VVA-003	892117.884	2028828.069	-40.154
VVA-004	888967.052	2030447.434	-39.887
VVA-005	891620.465	2027575.591	-35.793
VVA-006	871078.462	2004562.087	-19.219
VVA-007	881423.227	2006637.243	-32.695

Point ID	NAD83 (2011) UTM Zone 19 and 20		NAD83(2011) epoch:2010
	Easting X (m)	Northing Y (m)	Elevation (m)
VVA-011	855738.176	2025810.091	-40.764
VVA-074	288195.588	2030761.339	165.871
VVA-075	294373.402	2030354.056	353.494
VVA-076	299019.019	2028343.767	34.303
VVA-077	311608.900	2027738.054	80.070
VVA-078	317059.191	2028435.570	298.516
VVA-079	318969.830	2029594.670	-30.242
VVA-208	894165.947	2029942.375	80.047
VVA-210	847927.891	2014575.529	-11.549
VVA-239	811870.896	2042790.311	-39.644
VVA-241	855624.347	2031276.943	-37.325
VVA-247	842239.172	2010007.875	-38.372
VVA-248	838579.814	2001504.513	-23.111
VVA-249	856308.934	2033814.277	1.940
VVA-255	856084.622	2023384.582	-39.820
VVA-267	799179.685	1987365.977	-38.631
VVA-273	797311.823	2043537.062	-40.925
VVA-277	841778.146	2036888.586	-40.500
VVA-283	712245.618	1988503.808	-37.247
VVA-293	690865.205	1985956.054	-39.584
VVA-303	742540.539	2043856.902	-43.204
VVA-304	835348.677	1996016.056	-32.279
VVA-306	803908.780	1986664.924	-33.794
VVA-317	811771.809	1988615.878	-34.412
VVA-327	878316.412	2011424.735	-39.934
VVA-335	834799.810	2039945.654	-40.739
VVA-336	801987.830	2042767.175	-40.926
VVA-346	768756.717	1991089.226	-37.824
VVA-349	724705.264	1986370.030	-36.943
VVA-354	691144.477	1996613.920	-16.850
VVA-355	692402.328	1999509.534	-35.472
VVA-357	691790.071	2001226.059	-28.977
VVA-358	692248.853	2004168.283	-38.730
VVA-361	693477.370	2007885.138	-25.689
VVA-363	693886.799	2011546.382	-39.470
VVA-367	692995.841	2018627.366	-39.446
VVA-370	690392.662	2023537.608	-40.357
VVA-374	877636.600	2005307.549	-39.447
VVA-377	883733.267	2007240.881	-41.443
VVA-380	875630.331	2005229.070	-41.482
VVA-385	892738.792	2025401.075	-40.224

Point ID	NAD83 (2011) UTM Zone 19 and 20		NAD83(2011) epoch:2010
	Easting X (m)	Northing Y (m)	Elevation (m)
VVA-386	889164.793	2029709.232	-26.374
VVA-387	873718.331	2005114.729	-30.054
VVA-388	869685.183	2004284.451	-16.444
VVA-389	868208.541	2003207.812	-35.945
VVA-390	862349.455	2006722.989	-40.357
VVA-392	864264.599	2006744.200	-41.237
VVA-531	748313.961	2045619.694	-39.897
VVA-532	760828.838	1989438.332	-38.039
VVA-533	830078.581	1992409.003	-34.283
VVA-534	716436.096	1984796.589	-33.163
VVA-535	692359.674	1994676.636	-36.606
VVA-600	306498.954	1965056.520	-18.656
VVA-601	306641.468	1956505.582	-38.441
VVA-602	318877.730	2025302.990	-24.700
VVA-603	303087.330	2028938.642	-35.879
VVA-604	287806.433	2030095.978	190.799
VVA-605	895965.110	2029178.569	3.870
VVA-606	876005.848	2009887.601	-16.991
VVA-607	855748.344	2030514.280	-14.901
VVA-608	804078.497	2044409.176	-16.212
VVA-609	775018.417	2046396.879	-40.857
VVA-61	304126.997	1956574.288	-36.869
VVA-610	743039.527	2044871.580	-41.824
VVA-611	701781.760	2047897.607	-32.883
VVA-612	691769.494	2020482.500	-40.545
VVA-613	693750.141	1993046.269	-39.638
VVA-614	691502.618	1984921.521	-39.623
VVA-615	708898.489	1988918.253	-32.387
VVA-616	734392.977	1991536.211	-38.836
VVA-617	760696.627	1989249.448	-38.838
VVA-618	801575.243	1985223.217	-38.944
VVA-619	840199.964	2005278.412	-36.984
VVA-62	329694.240	1963655.977	-30.658
VVA-620	854947.599	2016114.006	-36.195
VVA-621	858773.827	2017371.947	-36.986
VVA-64	330956.288	1962990.216	-38.115
VVA-65	332016.160	1964060.152	-33.454
VVA-66	322648.777	1964206.402	-36.500
VVA-67	308196.941	1966186.864	-37.713
VVA-68	319408.887	1958210.121	-37.312
VVA-69	322449.357	1959427.834	-32.565

Table 8 – QAQC checkpoint locations.

Three checkpoints were removed from the vertical accuracy testing for the classified lidar due to environmental factors and survey errors. The coordinates of these checkpoints are provided in table 9 and photos and field logs showing the checkpoints are provided in figures 19–24.

Point ID	NAD83(2011) UTM Zone 18N		NAVD88 (Geoid 12B)		DeltaZ	AbsDeltaZ
	Easting X (m)	Northing Y (m)	Z-Survey (m)	Z-LiDAR (m)		
NVA-609	873397.893	2009408.581	-31.438	-31.650	-0.212	0.212
NVA-305	874380.894	2009403.891	-27.113	-27.340	-0.227	0.227
ST-310	766647.072	1990844.419	-40.197			

Table 9 – Checkpoints removed from vertical accuracy testing.

Figure 19 – Field photo for checkpoint NVA-609. Field photo shows the checkpoint should be located on a flat asphalt driveway, but final coordinates locate the checkpoint on a slope. Review by the surveyor deemed this survey checkpoint erroneous and unsuitable to use in the final vertical accuracy testing.

Dewberry

CHECK POINT DOCUMENTATION REPORT

Date: 4-27-2019 Time: 12:56 ☐ a.m. ☒ p.m. Employee Name: WES NEWMAN

Job Name: PR/VI Hurricane Maria Imagery and LiDAR CP Point ID: NVA-609

State: VIE 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: 4-28-19 Time: 1:49 ☐ a.m. ☒ p.m.

Re-Check Point ID: NVA-609RC

Description of Point:
SET NAIL IN PAVED ROAD

Sketch Area (NTS)

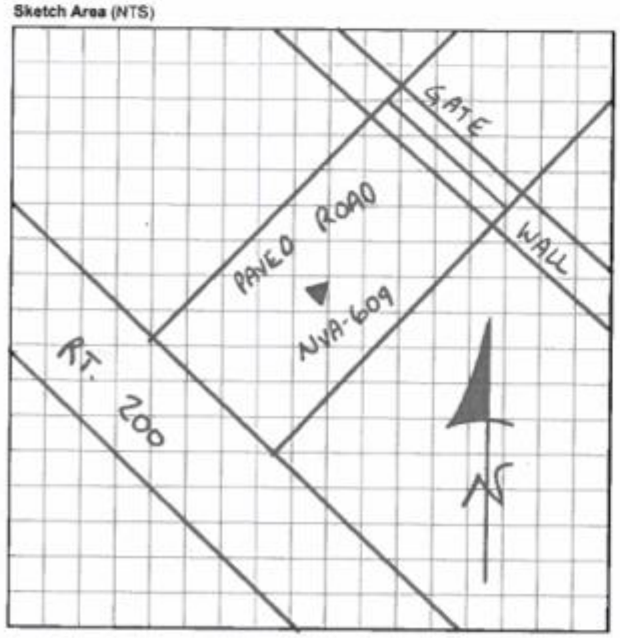

Figure 20 – Field sketch for checkpoint NVA-609.

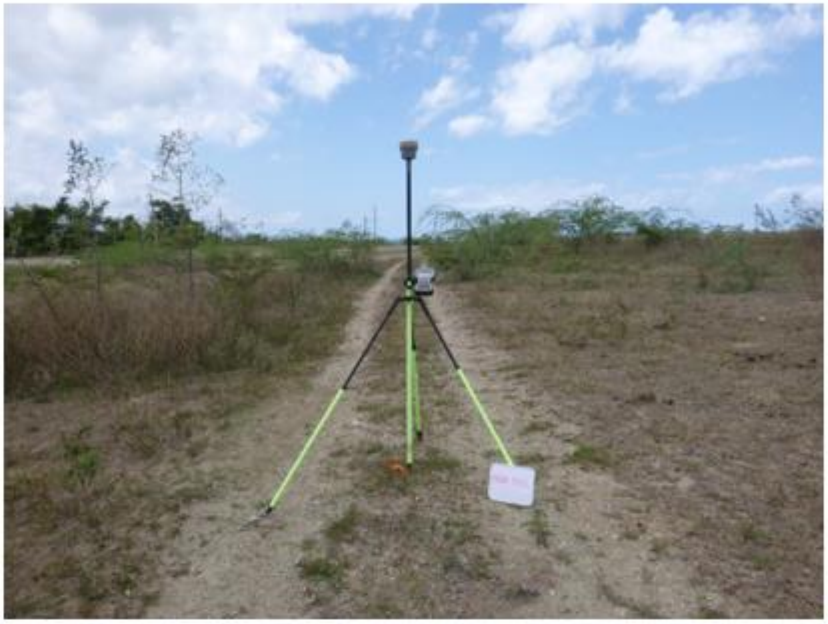

Figure 21 – Field photo for checkpoint NVA-305. Field photo shows the checkpoint should be located on a flat gravel pathway, but final coordinates place it on a slope in short grass. Review by the surveyor deemed this survey checkpoint erroneous and unsuitable to use in the final vertical accuracy testing.

Dewberry — CHECK POINT DOCUMENTATION REPORT

Date: 4-27-2019 Time: 12:45 ☐ a.m. ☒ p.m. Employee Name: WES NEWMAN

Job Name: PR/VI Hurricane Maria Imagery and LiDAR CP Point ID: NVA-305

State: VIE 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: 4-27-19 Time: 12:48 ☐ a.m. ☒ p.m.

Re-Check Point ID: NVA-305CK

Description of Point:
SET NAIL IN GRAVEL ROAD

Sketch Area (NTS)

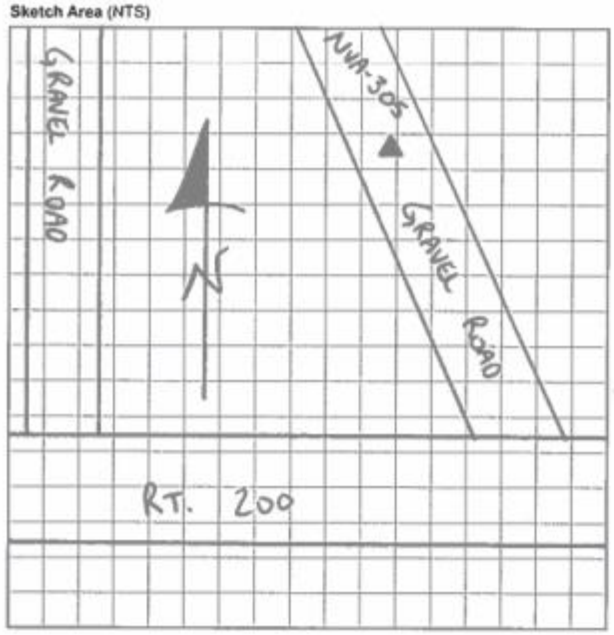

Figure 22 – Field sketch for checkpoint NVA-305.

Figure 23 – Field Photo for checkpoint ST-310. Field photo shows the checkpoint should be located within submerged topography, but final coordinates locate the checkpoint outside the project boundary.

Dewberry CHECK POINT DOCUMENTATION REPORT

Date: 4-3-2019 Time: 6:40 ☒ a.m. ☐ p.m. Employee Name: DAVID JAMESON

Job Name: PR/VI Hurricane Maria Imagery and LiDAR CP Point ID: ST-310

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
- ☒ ST

PICTURES

☑ Picture(s) of Area & Setup

POINT RE-CHECK

Date: 4-3-2019 Time: 6:44 ☒ a.m. ☐ p.m.

Re-Check Point ID: ST-310CK

Description of Point:
POINT SET IN 3.7' WATER ON HARD PACKED ROCKY BOTTOM (Small Rocks)

Sketch Area (NTS)

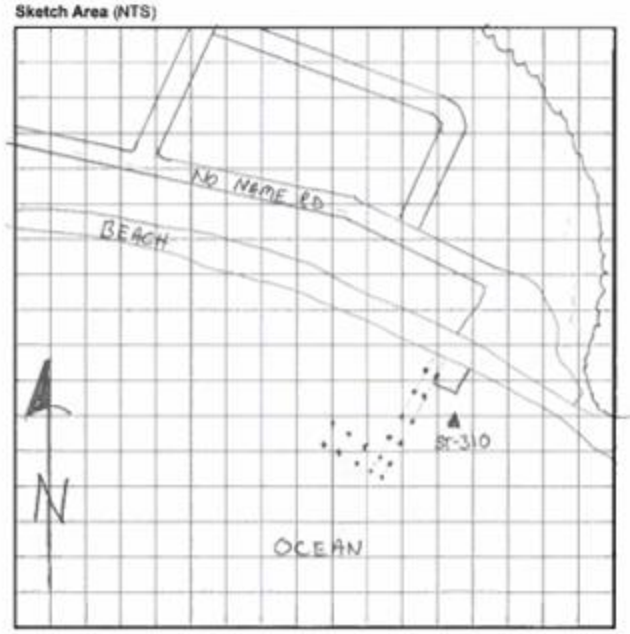

Figure 24 – Field sketch for checkpoint ST-310.

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 Puerto Rico and US Virgin Islands Topobathemetric Lidar Project, vertical accuracy must be 19.6 cm or less based on an $RMSE_z$ of 10 cm x 1.9600.

Bathymetric Vertical Accuracy is determined with check points located only in submerged topography. 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 Puerto Rico and US Virgin Islands Topobathemetric Lidar Project, bathymetric vertical accuracy must be 35.3 cm or less based on an $RMSE_z$ of 18 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 Puerto Rico and US Virgin Islands Topobathemetric 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 10.

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)
Bathymetric Vertical Accuracy in submerged topography using $RMSE_z$ *1.9600	35.3 cm (based on $RMSE_z$ (18 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 10 — Vertical accuracy 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 topobathy lidar DEM 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, bathymetric vertical accuracy 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

Table 11 summarizes the tested vertical accuracy resulting from a comparison of the surveyed checkpoints to the elevation values present within the fully classified lidar LAS files.

Land Cover Category	# of Points	NVA — Non-vegetated Vertical Accuracy (RMSEz x 1.9600) Spec=0.196 m	VVA — Vegetated Vertical Accuracy (95th Percentile) Spec=0.294 m	Bathymetric Vertical Accurracy (RMSEz x 1.9600) Spec=0.353 m
NVA	131	0.168		
VVA	94		0.251	
Bathymetric Vertical Accuracy	34			0.236

Table 11 — Tested vertical accuracy.

The topographic portion of this lidar dataset was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 10 cm RMSEz Vertical Accuracy Class. Actual NVA accuracy was found to be RMSEz = 8.6 cm, equating to ± 16.8 cm at 95% confidence level. Actual VVA accuracy was found to be ± 25.1 cm at the 95th percentile. The bathymetric portion of this lidar dataset was tested to meet the vertical RMSEz of QL2b specified in the Draft National Coastal Mapping Strategy 1.0 Document where vertical accuracy coefficients a and b are defined as 0.30 and 0.0130, respectively. Using the formula $\sqrt{(a2 + (b \times d)2)}$ where a equals constant depth errors, b equals depth dependent errors, and d equals depth, the bathymetric portion of this lidar dataset was tested to meet 30 cm RMSEz based on the depths of the surveyed submerged topography checkpoints. Actual bathymetric vertical accuracy was found to be RMSEz = 12.1 cm, equating to ± 23.6 cm at 95% confidence level.

Overall descriptive statistics for each land cover category are provided in table 12. Table 13 lists the VVA 5% outliers that are larger than the 95th percentile.

Point ID	NAD83 (2011) UTM Zone 19 and 20		NAD83(2011) epoch:2010	Lidar Z (m)	Delta Z	AbsDeltaZ
	Easting X (m)	Northing Y (m)	Survey Z (m)			
VVA-005	891620.465	2027575.591	-35.793	-35.420	0.373	0.373
VVA-208	894165.947	2029942.375	80.047	80.470	0.423	0.423
VVA-324	720999.361	1988454.022	-36.781	-36.430	0.351	0.351
VVA-606	876005.848	2009887.601	-16.991	-17.250	-0.259	0.259
VVA-80	299429.572	1963204.452	-24.064	-24.350	-0.286	0.286

Table 12 — VVA 5% outliers.

100 % of Totals	# of Points	RMSEz (m) Spec=0.100 m NVA/ 0.180 m Submerged Topography	Mean (m)	Median (m)	Skew	Std Dev (m)	Kurtosis	Min (m)	Max (m)
NVA	131	0.086	-0.047	-0.045	-0.089	0.072	0.243	-0.284	0.121
VVA	94	N/A	0.005	-0.013	0.882	0.114	2.979	-0.286	0.423
Submerged Topography	34	0.121	0.022	0.011	1.270	0.120	4.769	-0.237	0.466

Table 13 – Descriptive statistics.

Figure 25 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 -0.15 meters and a high of +0.7 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 -0.05 meters to +0.05 meters.

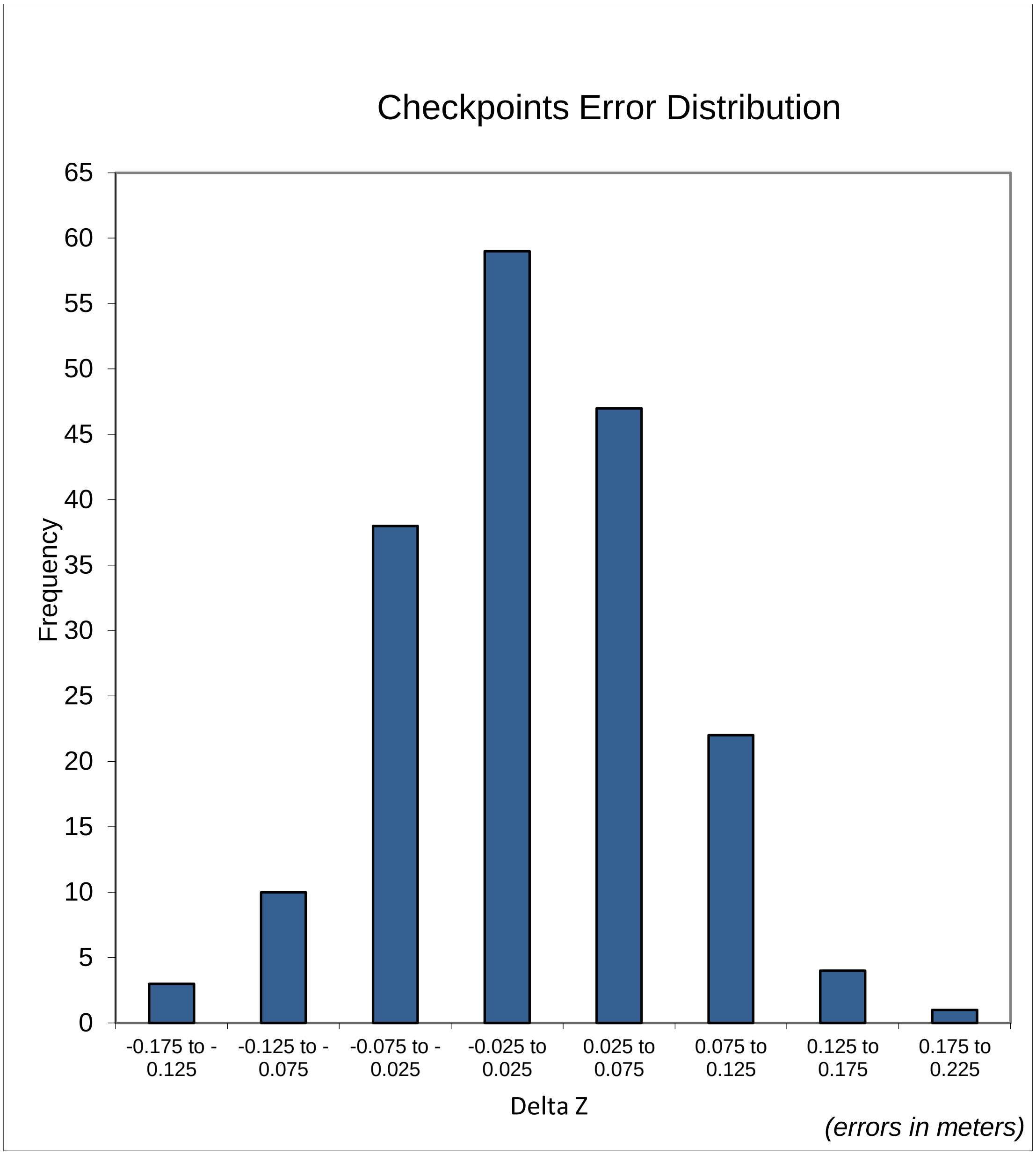

Figure 25 — Histogram of elevation discrepancies in meters.

Based on the vertical accuracy testing conducted by Dewberry, the lidar dataset for the NOAA PR1801-TB-C Topobathymetric 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 and PID 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

In addition to the vertical accuracy checkpoints collected for this project, Dewberry also collected 95 checkpoints determined to be on potentially photoidentifiable (PID) surfaces. Upon review of the survey data, 23 PID checkpoints as well as 8 NVA checkpoints were found to be placed at photoidentifiable locations suitable for horizontal accuracy testing.

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	$RMSE_x$ (Spec=0.409 m)	$RMSE_y$ (Spec=0.409 m)	$RMSE_r$ (Spec=0.578 m)	$ACCURACY_r$ ($RMSE_r$ x 1.7308) Spec=1 m
31	0.311	0.254	0.402	0.696

Table 14 - Tested horizontal accuracy at the 95% confidence level.

This data set was tested 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. Actual positional accuracy of this dataset was found to be RMSEx = 0.311 cm and RMSEy = 0.254 cm which equates to +/- 0.696 cm at 95% confidence level.

DEM Processing & Qualitative Assessment

The final topobathy DEMs are IMG format with 1 meter pixel cell size, tiled, and named according to project specifications. Void polygons were enforced in the DEMs so that bathymetric areas where no bathymetry was collected are NoData in the DEMs.

FINAL VOID POLYGONS

Final void polygons were created after all lidar edits and corrections were made. The void polygon layer was generated using LAStools 'las2dem' utility and ArcGIS to eliminate interpolation across areas 9 sq. m and greater the bathy class (40) in the final elevation raster. A user-defined threshold specifying the maximum allowable edge length during triangulation was set to 4 m, restricting rasterization in areas of sparse data. Once the constrained DEM was created, ArcGIS was used to vectorize the void (NoData) areas.

Once the final void polygons were created, they were used as a constraint to enforce voids (NoData) during the topobathymetric DEM creation.

DEM GENERATION

Digital elevation models were created using only ground (class 2) and submerged topography (class 40) lidar point data. A TIN was generated from these data and rasterized at a 1 m spatial resolution using LAStools 'blast2dem' utility. Void polygons (discussed previously) were used to eliminate large areas of interpolation in the DEM (≥ 9 sq. m). The DEM was clipped to the tile grid to create individual tiled DEMs that were named according to project specifications.

DEM QUALITATIVE REVIEW

Dewberry performed a comprehensive qualitative assessment of the topobathy DEM deliverables to ensure that all tiled DEM products were delivered with the proper extents and formatting, and contained the proper referencing information. This process was performed in ArcGIS with the use of a proprietary toolset.

The final topobathy DEMs were then reviewed in Global Mapper at a 1:3000 scale. A review with the void polygons visible and another review without the void polygons visible was performed in order to ensure voids were enforced properly and there were no issues along the boundaries of the void layer. Special attention was given along the land/water interface to ensure there were no hard edges along the interface (figure 26). Any remaining lidar issues and DEM artifacts were flagged by the reviewer and corrected by the editing team as necessary.

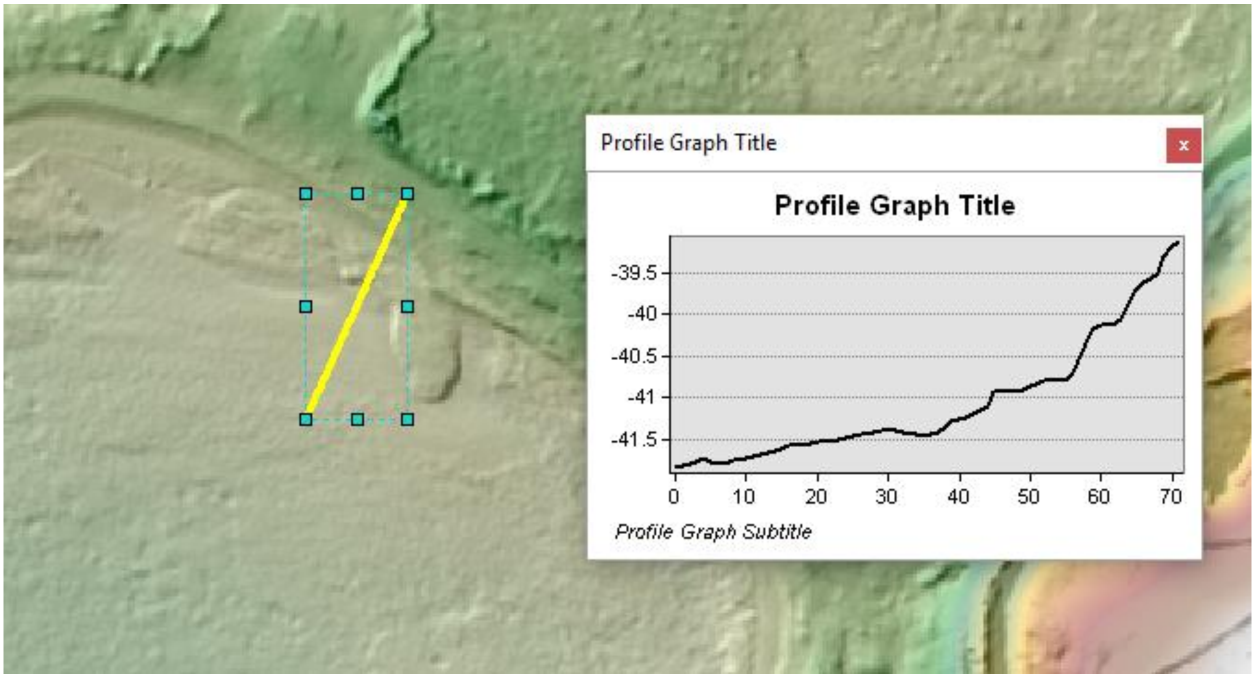

Figure 26 – DEM tile 2019_849300e_2014500n_dem. An example of the land-water interface is shown. No hard edges along the interface were identified during DEM QA/QC.

DEM QUANTITATIVE ASSESSMENT

The same 259 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.

The survey checkpoints used to test this topobathymetric dataset are listed in the survey report included as Appendix A.

Table 15 summarizes the tested vertical accuracy results from a comparison of the surveyed checkpoints to the elevation values present within the final DEM dataset.

Land Cover Category	# of Points	NVA — Non-vegetated Vertical Accuracy (RMSE$_z$ x 1.9600) Spec=0.196 m	VVA — Vegetated Vertical Accuracy (95th Percentile) Spec=0.294 m	Bathymetric Vertical Accuracy (RMSE$_z$ x 1.9600) Spec=0.353 m
NVA	131	0.169		
VVA	94		0.234	
Bathymetric Vertical Accuracy	34			0.265

Table 15 — DEM tested NVA and VVA.

The topographic portion of 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 RMSEz = 8.6 cm, equating to ± 16.9 cm at 95% confidence level. Actual VVA accuracy was found to be ± 23.4 cm at the 95th percentile. The bathymetric portion of this DEM dataset was tested to meet the vertical RMSEz of QL2b specified in the Draft National Coastal Mapping Strategy 1.0 Document where vertical accuracy coefficients a and b are defined as 0.30 and 0.0130, respectively. Using the formula $\sqrt{(a2 + (b \times d)2)}$ where a equals constant depth errors, b equals depth dependent errors, and d equals depth, the bathymetric portion of this DEM dataset was tested to meet 30 cm RMSEz based on the depths of the surveyed submerged topography checkpoints. Actual bathymetric vertical accuracy was found to be RMSEz = 13.5 cm, equating to ± 26.5 cm at 95% confidence level.

Overall descriptive statistics for each land cover category are provided in table 16. Table 17 lists the VVA 5% outliers that are larger than the 95th percentile.

Table 16 lists the 5% outliers that are larger than the VVA 95th percentile. Table 17 provides overall descriptive statistics.

Point ID	NAD83 (2011) UTM Zone 19 and 20		PRVD02 or VIVD09	DEM Z (m)	Delta Z	AbsDeltaZ
	Easting X (m)	Northing Y (m)	Survey Z (m)			
VVA-005	891620.465	2027575.591	-35.793	-35.420	0.373	0.373
VVA-208	894165.947	2029942.375	80.047	80.470	0.423	0.423
VVA-324	720999.361	1988454.022	-36.781	-36.430	0.351	0.351
VVA-606	876005.848	2009887.601	-16.991	-17.250	-0.259	0.259
VVA-80	299429.572	1963204.452	-24.064	-24.350	-0.286	0.286

Table 16 — VVA 5% outliers.

100 % of Totals	# of Points	RMSEz (m) Spec=0.1 m NVA/0.185 m Bathy Bottom	Mean (m)	Median (m)	Skew	Std Dev (m)	Kurtosis	Min (m)	Max (m)
NVA	131	0.086	-0.043	-0.043	0.274	0.075	1.329	-0.284	0.240
VVA	94	N/A	0.010	-0.003	0.808	0.112	2.897	-0.269	0.418
Submerged Topography	34	0.135	0.029	0.011	2.221	0.134	8.793	-0.182	0.594

Table 17 — DEM accuracy descriptive statistics.

Based on the vertical accuracy testing conducted by Dewberry, the DEM dataset for the NOAA PR1801-TB-C Topobathymetric Lidar Project satisfies the project's pre-defined vertical accuracy criteria.

DEM CHECKLIST

Table 18 represents a portion of the high-level steps in Dewberry's DEM Production and QA/QC checklist that were performed for this project.

Pass/Fail	Validation Step
Pass	Final void polygons are created
Pass	LASTools utilities and void polygons are used to create the final topobathymetric model using project specifications for grid type, formatting, and cell size
Pass	Manually review topobathymetric DEMs to check for issue
Pass	Special attention should be paid along the land/water interface
Pass	DEMs should be seamless across tile boundaries
Pass	Bridges should NOT be present in final topobathy DEMs.
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, Bathymetric Vertical Accuracy 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 18 – A subset of the high-level steps from Dewberry's bare earth DEM Production and QA/QC checklist performed for this project.

Metadata

Project level metadata files were delivered in XML format for all project deliverables including lidar, DEMs, land/water interface breaklines, and void polygons. All metadata files are FGDC compliant and were verified to be error-free according to the USGS MetaParser.

Appendix A : Checkpoint Survey Report

Appendix B: Ground Control Point Survey Report

Appendix C: Complete List of Delivered Tiles

2019_683300e_2034500n_las
2019_684300e_2034500n_las
2019_685300e_2034500n_las
2019_686300e_2034500n_las
2019_687300e_2034500n_las
2019_688300e_2034500n_las
2019_689300e_2034500n_las
2019_690300e_2034500n_las
2019_691300e_2034500n_las
2019_686300e_2035500n_las
2019_687300e_2035500n_las
2019_688300e_2035500n_las
2019_689300e_2035500n_las
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2019_693300e_2044500n_las	2019_848300e_2033500n_las	2019_669300e_1992500n_las	2019_780300e_2045500n_las
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2019_692300e_2045500n_las	2019_859300e_2033500n_las	2019_680300e_1992500n_las	2019_791300e_2045500n_las
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2019_722300e_2045500n_las	2019_873300e_2033500n_las	2019_694300e_1992500n_las	2019_805300e_2045500n_las
2019_723300e_2045500n_las	2019_874300e_2033500n_las	2019_695300e_1992500n_las	2019_806300e_2045500n_las
2019_724300e_2045500n_las	2019_875300e_2033500n_las	2019_668300e_1993500n_las	2019_807300e_2045500n_las
2019_725300e_2045500n_las	2019_876300e_2033500n_las	2019_669300e_1993500n_las	2019_808300e_2045500n_las
2019_726300e_2045500n_las	2019_877300e_2033500n_las	2019_670300e_1993500n_las	2019_809300e_2045500n_las
2019_727300e_2045500n_las	2019_878300e_2033500n_las	2019_671300e_1993500n_las	2019_810300e_2045500n_las
2019_728300e_2045500n_las	2019_879300e_2033500n_las	2019_672300e_1993500n_las	2019_811300e_2045500n_las
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2019_730300e_2045500n_las	2019_845300e_2034500n_las	2019_674300e_1993500n_las	2019_813300e_2045500n_las
2019_731300e_2045500n_las	2019_846300e_2034500n_las	2019_675300e_1993500n_las	2019_814300e_2045500n_las
2019_732300e_2045500n_las	2019_847300e_2034500n_las	2019_676300e_1993500n_las	2019_815300e_2045500n_las
2019_733300e_2045500n_las	2019_848300e_2034500n_las	2019_677300e_1993500n_las	2019_816300e_2045500n_las
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2019_736300e_2045500n_las	2019_851300e_2034500n_las	2019_680300e_1993500n_las	2019_819300e_2045500n_las
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2019_712300e_1984500n_las	2019_326479e_1959500n_las	2019_697300e_1984500n_las	2019_311479e_1959500n_las
2019_713300e_1984500n_las	2019_327479e_1959500n_las	2019_698300e_1984500n_las	2019_312479e_1959500n_las
2019_714300e_1984500n_las	2019_328479e_1959500n_las	2019_699300e_1984500n_las	2019_313479e_1959500n_las
2019_715300e_1984500n_las	2019_329479e_1959500n_las	2019_700300e_1984500n_las	2019_314479e_1959500n_las
2019_716300e_1984500n_las	2019_331479e_1959500n_las	2019_701300e_1984500n_las	2019_315479e_1959500n_las
2019_717300e_1984500n_las	2019_332479e_1959500n_las	2019_719300e_1984500n_las	2019_297479e_1960500n_las
2019_718300e_1984500n_las	2019_296479e_1960500n_las	2019_326479e_1971500n_las	

Appendix D: GPS Processing Reports