Lidar Mapping Report

PR_PuertoRicoUSVI_6_D24 | Delivery Block 6

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1. Data Acquisition and Processing

The PR_PuertoRicoUSVI_D24 task is for high-resolution data set of QL1 lidar (≥8 pts/m2) covering approximately 3,586 square miles in Puerto Rico and the US Virgin Islands. The PR_PuertoRicoUSVI_D24 project will support the United States Geological Survey (USGS) and their partners by providing high-quality topographic data critical to making decisions. This project will support the 3DEP mission, the Natural Resources Conservation Service (NRCS) high resolution elevation enterprise, and many local agencies.

The lidar data and derivative products produced in compliance with this task order will be based on the National Geospatial Program Lidar Base Specification 2024, Revision A.

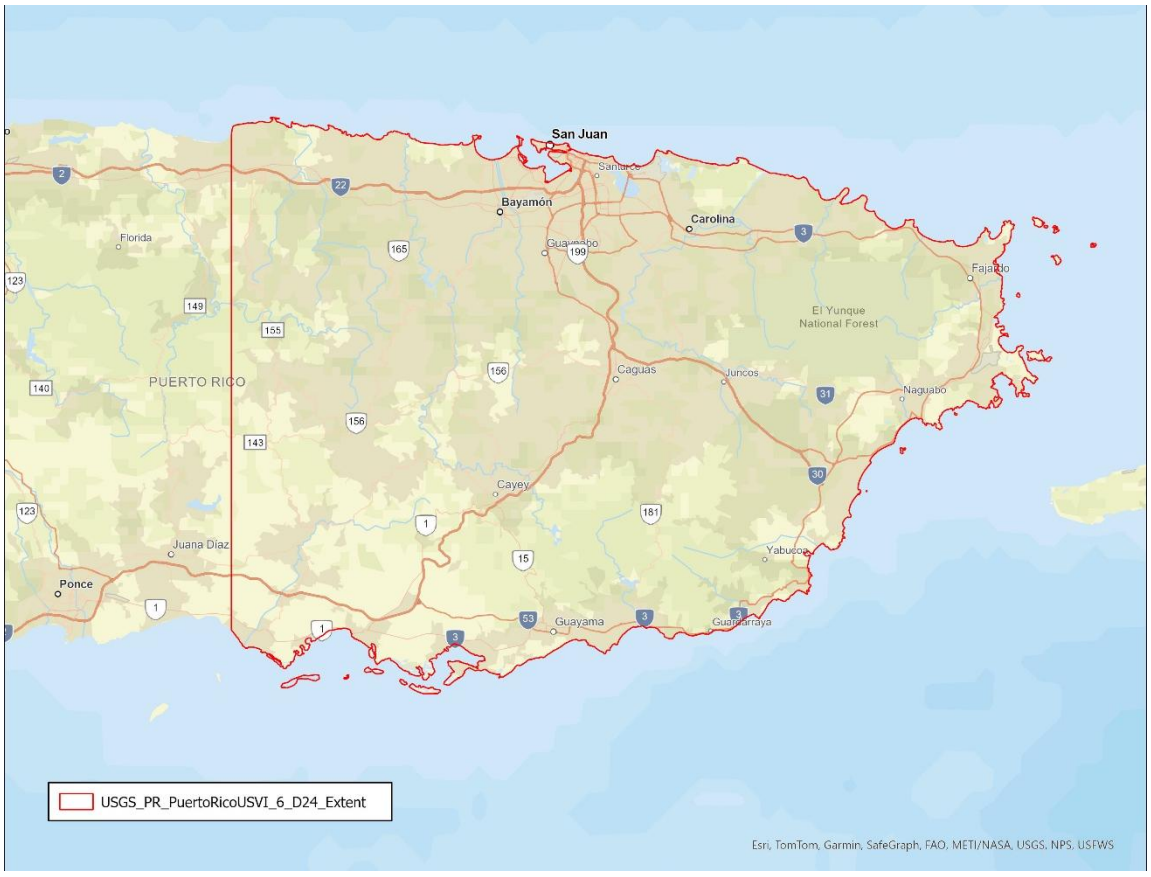


Figure 1: Work Unit Extent

1.1 Sensor

1.1.1 Settings

This Block was collected using the Riegl VQ-1560 II-S sensor using the following parameters/settings:

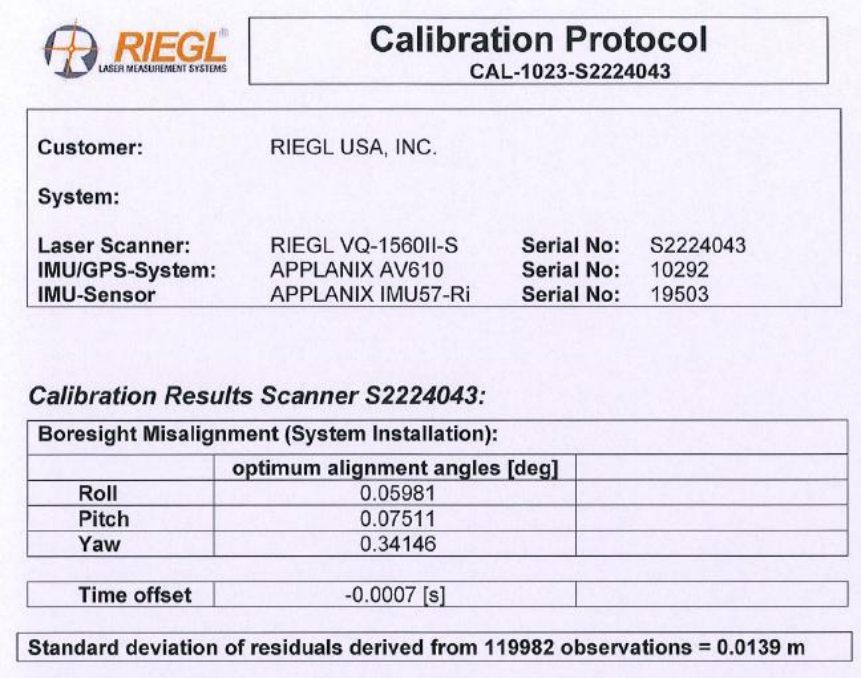
Riegl VQ-1560 II-S:

- Aggregate Nominal Pulse Spacing (ANPS): ≥0.35 Meters; ≥8 pts/m2 (QL1)
- Scan Angle: 58.52 degrees
- Pulse Rate: 2,302,000 Hz (2 x 1151 kHz)
- Scan Rate: 332 (2 x 166)
- Swath Width: 7,283' (2,220 meters)
- Sidelap: 55%
- Flight Height: 6,500' AMT (1981 meters)
- Flight Speed: 165 knots

NOTE: This project was planned with additional sidelap and higher density to compensate for high relief and heavy vegetation. The actual achieved point density may be up to 40-45 pts/m2.

1.1.2 Calibration

The Roll-Pitch-Yaw correction (standard boresight) for each swath is applied on a collection or block basis (see Section Boresight Calibration). Additionally, the sensors are sent to the manufacturer every 2-3 years to perform internal calibrations, along with data from a calibration flight over known targets, to correct for gradual loss of alignment between channels 1 & 2. These internal calibration results are then applied to the system before subsequent collections.



RIEGL LASER MEASUREMENT SYSTEMS

Calibration Protocol
CAL-1023-S2224043

Customer:	RIEGL USA, INC.		
System:			
Laser Scanner:	RIEGL VQ-1560II-S	**Serial No:**	S2224043
IMU/GPS-System:	APPLANIX AV610	**Serial No:**	10292
IMU-Sensor	APPLANIX IMU57-Ri	**Serial No:**	19503

Calibration Results Scanner S2224043:

Boresight Misalignment (System Installation):		
	optimum alignment angles [deg]	
Roll	0.05981	
Pitch	0.07511	
Yaw	0.34146	

Time offset	-0.0007 [s]	

Standard deviation of residuals derived from 119982 observations = 0.0139 m

Figure 2: Manufacturer calibration / certificates

1.2 Verification of Data Usability

All acquired lidar data went through a preliminary review to assure that complete coverage had been obtained and that there were no gaps between flight lines before the flight crew left the project site. Once back in the office, the data was run through a complete iteration of processing to ensure that it is complete, uncorrupted, and that the entire project area has been covered without gaps between flight lines. There are essentially three steps to this processing.

1.2.1 GNSS-IMU Processing

Airborne GNSS-IMU data was processed using POSPac 8.7 PP-RTX. This processing technique uses a web based GNSS correction service that utilizes a global network of tracking stations to compute corrections of satellite ephemeris, clock information and atmospheric models. Using this method, we achieved cm-level trajectory accuracy without the use of local base-stations.

GNSS-IMU Processing Datum: WGS84 exported into NAD83 (2011)

Base-Stations: n/a

Please see metadata\reports\lidar_mapping_report\GNSS_Reports for graphics of processed plots for each lift.

1.2.2 Raw Lidar Data Processing

Technicians processed the raw data to LAS format flight lines with full resolution output before performing QC. A starting configuration file is used in this process, which contains the latest calibration parameters for the sensor. The technicians also generated flight line trajectories for each of the flight lines during this process.

1.2.3 Verification of Coverage and Data Quality

The following steps and quality control measures are performed to verify complete coverage and ensure data quality:

- Trajectory files were checked to ensure completeness of acquisition for the flight lines, calibration lines, and cross flight lines.
- Intensity images were generated for the entire lift at the required 0.35m aggregate nominal post spacing (ANPS). Visual checks of the intensity images against the project boundary were performed to ensure full coverage to the project boundary.
- The intensity histogram was analyzed to ensure the quality of the intensity values.
- A thorough review of the data was performed to identify any data gaps in project area. Technicians visually inspected the data and confirmed that no voids greater than or equal to (4 × ANPS)2, were present in the first returns.
- A sample TIN surface was generated to ensure no anomalies are present in the data.
- Turbulence was inspected for each flight line. If any adverse quality issues were discovered, the flight line was rejected and re-flown.
- The achieved post spacing was evaluated against the project specified 0.35m ANPS using RiProcess and Batchpack to produce density Tiffs with a 10x10 grid size and checked to make sure there is no clustering in point distribution. Aggregate Nominal Pulse Density (ANPD) was confirmed be no less than 8 points per square meter (QL1) and Aggregate Nominal Pulse Spacing (ANPS) was confirmed be no greater than 0.35 meters (QL1); this assessment was made against single swath, first return data located within the geometrically usable center portion of each swath.

- This Work Unit was collected in 34 missions on 33 separate dates:

December 27, 2023	January 23, 2024	March 9, 2024	February 17, 2025
December 29, 2023	January 29, 2024	March 11, 2024	February 21, 2025
January 3, 2024	February 9, 2024	March 18, 2024	February 27, 2025
January 4, 2024	February 12, 2024	March 20, 2024	March 9, 2025
January 5, 2024	February 16, 2024	March 28, 2024	March 10, 2025
January 7, 2024	February 18, 2024	March 30, 2024	March 20, 2025
January 11, 2024	February 23, 2024	April 4, 2024	
January 19, 2024	February 24, 2024	April 6, 2024	
January 21, 2024	March 5, 2024	April 7, 2024	

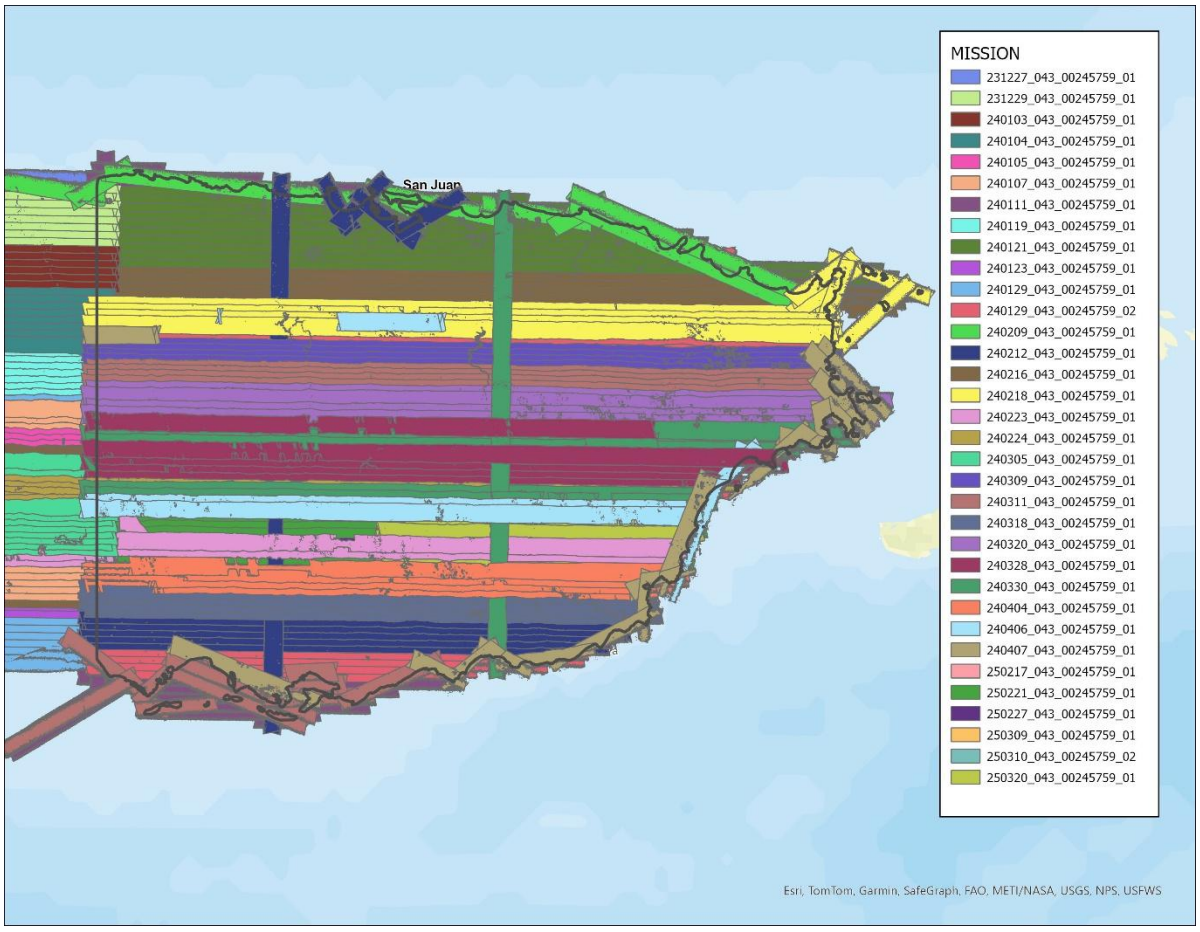


Figure 3: Flightline vectors

1.2.4 Cloud Data Gaps

Some locations could not be acquired without cloud cover, even after multiple attempts and reflights. These areas were approximately identified during the acquisition phase. The areas have been further refined throughout the post-production process and are <0.04 sq km. The areas are identified in a shapefile included with the spatial metadata: USGS_PR_PuertoRicoUSVI_6_D24_EastMainland_SurfaceGaps.shp

2. Lidar Data Processing

Data processing includes the following four (4) production steps for generating the final deliverables:

1. Raw data processing and boresight
2. Pre-processing
3. Post-processing
4. Product development

Quality control steps are incorporated throughout each step and are described in the following sections.

2.1 Raw Data Processing and Boresight Calibration

Raw data processing is the reduction of raw lidar, IMU, and GNSS data into XYZ points. This is a hardware-specific, vendor-proprietary process. The raw lidar data processing algorithms use the sensor's complex set of electronic timing signals to compute ranges or distances to a reflective surface. The ranges must be combined with positional information from the GNSS/IMU system to orient those ranges in 3D space and to produce XYZ points.

2.1.1 Boresight Calibration

The boresight for each lift was done individually as the solution may change slightly from lift to lift. The following steps describe the Raw Data Processing and Boresight Calibration process:

- Technicians processed the raw data to LAS format flight lines using the final GNSS/IMU solution. This LAS data set was used as source data for boresight.
- Technicians first used Fugro proprietary and commercial software to calculate initial boresight adjustment angles based on sample areas within the lift. These areas cover calibration flight lines collected in the lift, cross tie, and production flight lines (see figure below). These areas are well distributed in the lift coverage and cover multiple terrain types that are necessary for boresight angle calculation. The technician then analyzed the results and made any necessary additional adjustment until it is acceptable for the selected areas. The boresight angle

adjustment process ensures proper alignment between different look angles as well as between flight line overlaps.

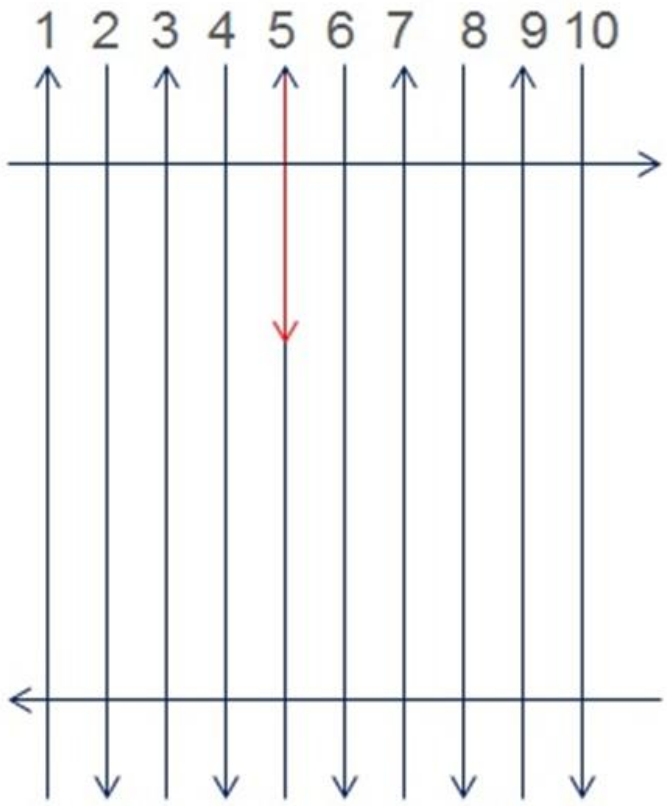


Figure 4: Example production block: North-south are production lines, east-west are cross ties, calibration flight line shown in red.

- Once the boresight angle calculation was completed for the selected areas, the adjusted settings were applied to all the flight lines of the lift and checked for consistency. The technicians utilized commercial and proprietary software packages to analyze the matching between flight line overlaps for the entire lift and adjusted as necessary until the results met the project specifications.
- Once all lifts were completed with individual boresight adjustment, the technicians checked and corrected the vertical misalignment of all flight lines and the matching between data and ground truth. The relative accuracy was ≤ 6 cm within individual swaths (smooth surface repeatability) and ≤ 8 cm RMSD within swath overlap (between adjacent swaths) with a maximum difference of ± 16 cm.

- The technicians ran a final vertical accuracy check of the boresighted flight lines against the surveyed check points after the z correction to ensure the requirement of $RMSE_V$ (non-vegetated) ≤ 10 cm was met.

2.2 Pre-processing

Once boresighting was complete for the project and all lifts were tied to the ground control, the project was set up for filtering. The lidar data was cut to production tiles for editing purposes.

2.3 Post-processing

Fugro has developed a unique method for processing lidar data.

Once boresighting was complete for the project, the project was first set up for automatic classification. The lidar data was cut to production tiles. The low noise points, high noise points and ground points were classified automatically in this process. Fugro utilized commercial software, as well as proprietary, in-house developed software for automatic filtering. The parameters used in the process were customized for each terrain type to obtain optimum results.

Once the automated filtering was completed, the files were run through a visual inspection to ensure that the filtering was not too aggressive or not aggressive enough. In cases where the filtering was too aggressive and important terrain were filtered out; the data was either run through a different filter within local area or was corrected during the manual filtering process. Bridge deck points were classified as well during the interactive editing process. Interactive editing was completed in visualization software that provides manual and automatic point classification tools. Fugro utilized commercial and proprietary software for this process. All manually inspected tiles went through a peer review to ensure proper editing and consistency.

After the manual editing and peer review, all tiles went through another final automated classification routine. This process ensures only the required classifications are used in the final product (all points classified into any temporary classes during manual editing will be reclassified into the project specified classifications).

2.4 Product Development

After the lidar went through all initial processing and was checked for quality, we began the process of derivative product development to the project requirements and specifications.

2.4.1 Classified Point Cloud Data

Once manual inspection, QC and final auto filter is complete for the lidar tiles, the LAS data was packaged to the project specified tiling scheme, clipped to project boundary, and formatted to LAS v1.4. It was delivered the following spatial reference system: NAD83 (2011) Puerto Rico & Virgin Is., Meters, PRVD02 (GEOID18), Meters. The file header was formatted to meet the project specification with File Source ID assigned. This Classified Point Cloud product was used for the generation of derived products. Water points were classified to Class 9 and Ignored ground points

were classified to Class 20 using the collected hydro breaklines. Withheld tags were used on noise points above and below the surface and were assigned by a Terrascan macro.

This product was delivered in fully compliant LAS v1.4, Point Record Format 6 with Adjusted Standard GPS Time at a precision sufficient to allow unique timestamps for each pulse. Correct and properly formatted georeference information as Open Geospatial Consortium (OGC) well known text (WKT) was assigned in all LAS file headers. Each tile has unique File Source ID assigned. The Point Source ID matches to the flight line ID in the flight trajectory files. Intensity values are included for each point, normalized to 16-bit.

The following classifications are included:

(1) Class 1 – Processed, but unclassified

(2) Class 2 – Bare earth ground

(03) Class 7 – Low Noise

(04) Class 9 – Water

(05) Class 17 – Bridge Decks

(06 Class 18 – High Noise

(07) Class 20 – Ignored Ground (Breakline Proximity)

(08) Class 21 – Snow (if present and identifiable)

(09) Class 22 – Temporal Exclusion (typically non-favored data in intertidal zones, use as necessary)

The classified point cloud data was delivered in tiles without overlap using the project tiling scheme.

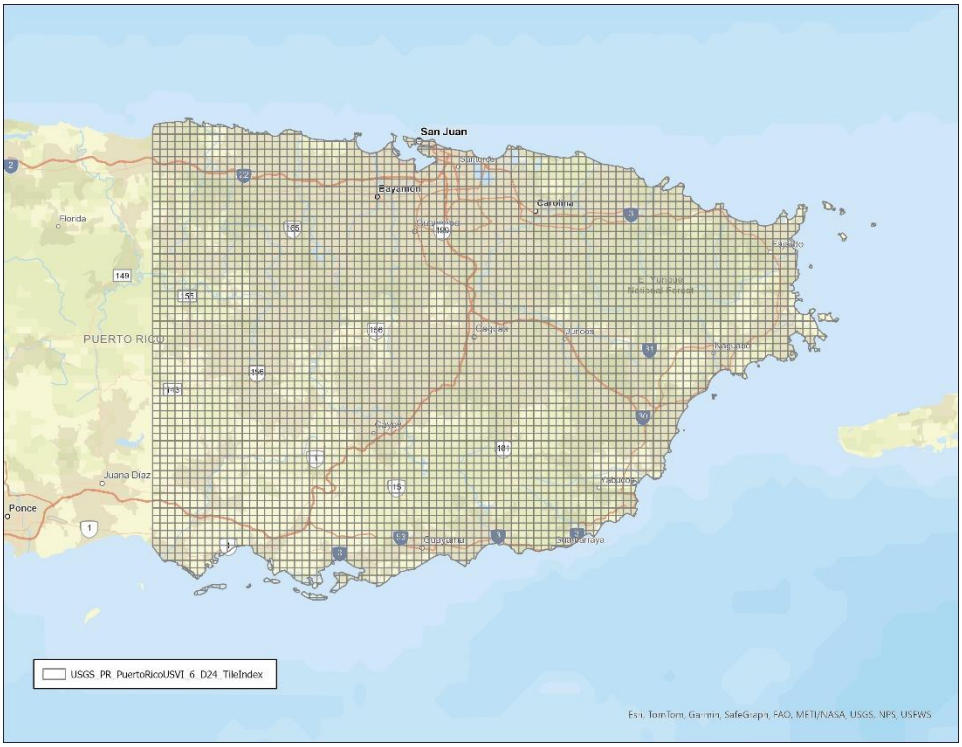


Figure 5: Delivery Block Tiles

2.4.2 Bare Earth Surface (Raster DEM)

The bare earth DEM was generated using the lidar bare earth points and 3D hydro breaklines to a resolution of 0.5 meters. Where needed, supplemental breaklines were collected and used in DEM generation under the bridges to ensure a logical terrain surface below a bridge. If applicable, this layer will be included in the delivered hydro breaklines geopackage.

The bare earth points that fell within 1*ANPS along the hydro breaklines (points in class 20) were excluded from the DEM generation process. This is analogous to the removal of mass points for the same reason in a traditional photogrammetrically compiled DTM. This process was done in batch using proprietary software.

The technicians then used Fugro proprietary software to produce the lidar-derived hydro flattened bare earth DEM surface in initial grid format at 0.5 meters GSD. The DEM creation software function drapes each DEM cell to TIN surface created in memory to calculate each cells Z value. The interpolation method is 3D linear interpolation (trilinear) based on a TIN of classified ground points.

Water bodies (inland ponds and lakes), inland streams and rivers, and island holes were hydro flattened within the DEM. Hydro flattening was applied to all water impoundments, natural or man-made, that are larger than approximately 2 acres in area, to all streams that are nominally wider than 30 meters (~100 feet), and to all non-tidal boundary waters bordering the project area, regardless of size. This process was done in batch.

Once the initial, hydro flattened bare earth DEM was generated, the technicians checked the tiles to ensure that the grid spacing met specifications. The technicians also checked the surface to ensure proper hydro flattening. The entire data set was checked for complete project coverage. Once the data was checked, the tiles were then converted to GeoTiff format. GDAL version 3.4.1 was used to define the raster coordinate reference system. Georeference information is included in the raster files. Void areas (i.e., areas outside the project boundary but within the tiling scheme) are coded using a unique "NODATA" value.

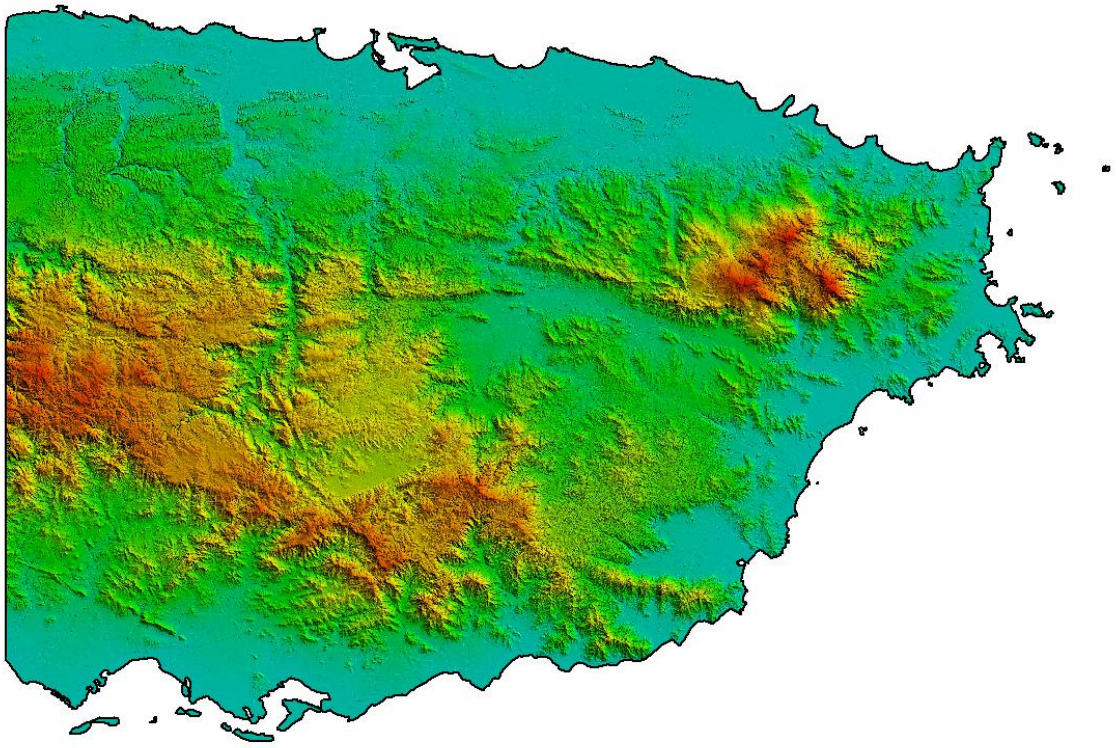


Figure 6: Delivery Block Shaded Relief

2.4.3 Maximum Surface Height Rasters

Fugro used a proprietary tool to create maximum surface height rasters (MSHR). Fugro used the MSHR to assess withheld flagging of the Lidar Point Cloud. MSHRs are created from the highest non-withheld point in the LPC in each pixel. The output file format delivered were GeoTIFF at a resolution of 1 meter.

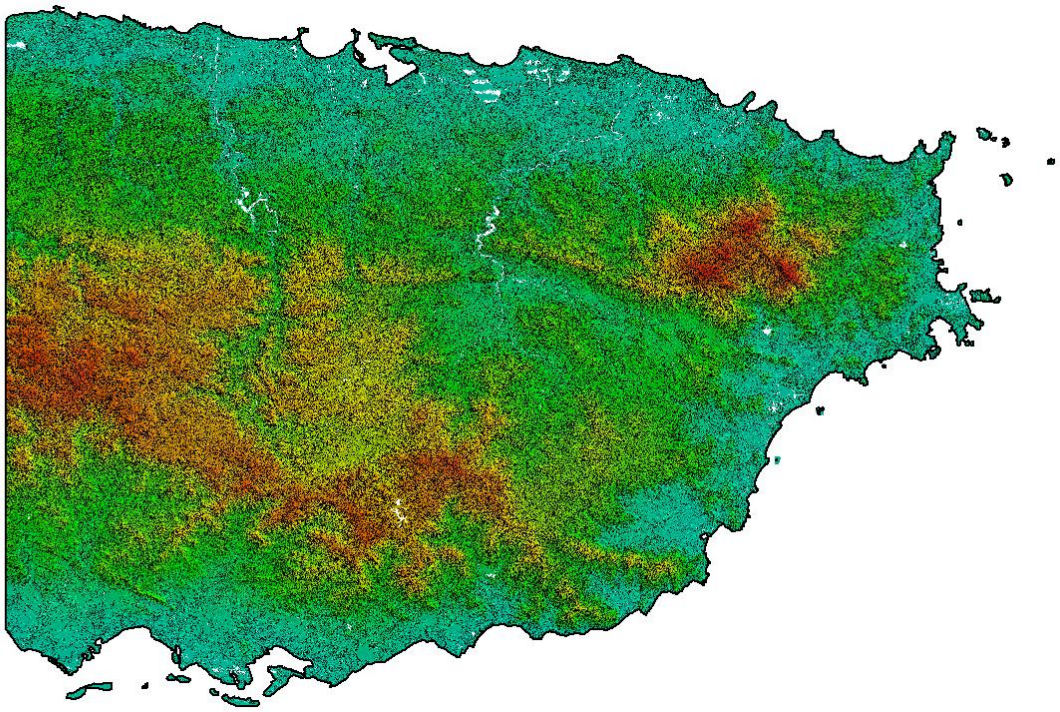


Figure 7: Maximum Surface Height Rasters

2.4.4 Lidar Hydro Breakline Collection

Hydro linework is produced by heads-up digitizing using classified lidar datasets in ArcGIS 10.6.1 with a LP360 overlay package to display, shaded relief tin, intensities, and contours.

Additionally, products created from lidar including intensity images, shaded-relief TIN surfaces, and contours are used.

Hydrographic features were collected as separate feature classes:

Inland Ponds and Lakes

- ~2-acre or greater surface area (~100-meter diameter for a round pond), and ~0.5-acre islands.
- Flat and level water bodies (single elevation for every bank vertex defining a given water body).
- The entire water surface edge must be at or just below the immediately surrounding terrain.
- Long impoundments such as reservoirs, inlets, and fjords, whose water surface elevations drop when moving downstream, were treated as rivers.

Inland Streams and Rivers

- 100’ nominal width: short segments that narrowed to 65’ and back to100’ for a ½ mile stretch, were captured to avoid unnecessary segmentation.

- Flat and level bank-to-bank (perpendicular to the apparent flow centerline); gradient to follow the immediately surrounding terrain.
- The entire water surface edge is at or just below the immediately surrounding terrain.
- Streams break at road crossings (culvert locations). These road fills were not removed from the DEM. Streams and rivers do not break at bridges. Bridges were removed from the DEM. When the identification of a feature as a bridge or culvert could not be made reliably, the feature was regarded as a culvert.
- The bare earth surface below a bridge is a continuous logical interpolation of the apparent terrain lateral to the bridge deck. Where abutments are clearly visible, the bare earth interpolation begins at the junction of the bridge deck and approach structure. Where this junction is not clear, Fugro utilized their professional judgment to delineate the separation of below-bridge terrain from elevated bridge surface.
- No geometric changes were made to the originally computed lidar points. Bare earth lidar points that are near breaklines were classified as Ignored Ground and excluded from the DEM generation process.
- Streams, rivers, and water bodies meeting the criteria for hydro flattening are monotonically continuous where bridge decks have been removed.
- All breaklines used to enforce a logical terrain surface below a bridge were delivered as a separate shapefile and delivered with the hydro product.

Non-Tidal Boundary Waters

- Represented only as an edge or edges within the project area; collection does not include the opposing shore.
- The entire water surface edge is at or below the immediately surrounding terrain.
- The elevation along the edge or edges behaves consistently throughout the project.

2D Topological QC: After initial collection Linework was then checked for the following topological and attribution rules:

- Lines must be attributed with the correct feature code (River, Lake, etc.).
- Lake and stream banklines (River) must form closed polygons, with no overlaps or anomalies.

3D Attribution: Hydro features were collected as vector linework using lidar and its derived products listed above. This linework is initially 2D, meaning that it does not have elevation values assigned to individual line vertices. Vertex elevation values were assigned using a distance weighted distribution of lidar points closest to each vertex. This is similar to draping the 2D linework to a surface modeled from the lidar points. After the initial 'drape,' the linework elevation values were further adjusted based on the following rules:

- Lake feature vertices were re-assigned (flattened) to lowest draped vertex value.
- Double stream bankline vertices were re-assigned based on the vertices of the closest adjusted double stream connector line.
- Proprietary profile tool was used to QC bank-to-bank flatness, monotonicity, and lake flatness.

The hydro breaklines were delivered in Geopackage format.

2.4.5 Intensity Images

Upon the completion of lidar point cloud product creation, First Return points were used for intensity image generation automatically. The software considers points from neighboring tiles while creating the images for seamless edge matching. The initial intensity images were generated at 0.5 meter resolution in 16 bit TIFF format. They were then converted to 8 bit format. Georeferencing information was assigned to all images. The technician QC'ed the final intensity images before delivery. The intensity images were delivered in GeoTIFF format.

Figure 8: Intensity Images

2.4.6 Low Confidence Polygons

Low confidence polygons have been delivered with this dataset. These polygons represent areas where heavy vegetation affects the 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 (despite the additional sidelap and higher density overall density achieved on this project). Sparse ground returns are being defined as any 10x10 meter radius with zero ground

returns. Voids are calculated and converted to vector directly from the point cloud. The point density rasters are used as a visual QC, in case of false positives.

3. Accuracy reporting

Data collected under this Task Order meets the ASPRS Positional Accuracy Standards for Digital Geospatial Data, Edition 2, Version 1.0. The ASPRS standards specify that vertical accuracy be tested by comparing the elevations of the surface represented by the data set with elevations determined from an independent source of higher accuracy.

3.1 Positional Accuracy

Before classification and development of derivative products from the point cloud, the absolute and relative vertical accuracies of the point cloud were verified.

3.2 Horizontal Accuracy

This data set was produced to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data, Edition 2 (2023) for a 18.9 cm $RMSE_H$ horizontal positional accuracy class.

3.3 Absolute Vertical Accuracy

Unclassified Lidar Point Cloud Data: The Non-Vegetated Vertical Accuracy (NVA) of the Lidar Point Cloud data was calculated against TINs derived from the final calibrated and controlled swath data. The required accuracy (ASPRS 2023) is $RMSE_V$ of $\leq$10 cm in the "open terrain" and/or "urban" land cover categories. This is a required accuracy. Please refer to the table below for the achieved accuracies. The raw swath point cloud data met the required accuracy levels before point cloud classification and derivative product generation.

Note: NVA checkpoints 42 and 64 were excluded from the unclassified point cloud assessment, due to nearby obstructions in the unclassified data.

Table 1: Accuracy of the Unclassified (Raw) Lidar Point Cloud Data

Unclassified Point Cloud	Achieved accuracy
RMSEv specification [m]	≤ 0.100
RMSEv calculated values [m]	0.05
Number of points	40
Maximum error [m]	0.088
Minimum error [m]	-0.072
Mean Error [m]	0.009
Median error [m]	0.009
Standard deviation [m]	0.039

Bare Earth Surface: The accuracy of the classified point cloud data and the derived DEM were calculated and are being reported in two (2) ways:

1. **$RMSE_V$ Non-Vegetated Vertical Accuracy (NVA):** The required RMSEV (ASPRS 2023) is ≤ 10 cm in the "Open terrain" and/or "Urban" land cover categories. The calculated $RMSE_V$ also factors in the survey accuracy of the NVA points.

2. **$RMSE_V$ Vegetated Vertical Accuracy (VVA):** The VVA $RMSE_V$ accuracy is reported as found in Vegetated land cover categories combined (Tall Grass, Brush, Forested Areas). There is no pass/fail requirement for VVA. The calculated $RMSE_V$ also factors in the survey accuracy of the VVA points.

We calculated Non-vegetated and Vegetated vertical accuracy against TINs derived from the final calibrated, controlled, tiled, and ground classified lidar point cloud data. The Non-Vegetated Vertical Accuracy and Vegetated Vertical Accuracy were also calculated for the derived DEM. Please refer to Table 2 and 3 below for the achieved accuracies within project AOI.

Note: VVA 17 and VVA 21 were excluded in the LAS assessment, due to lack of ground points within the search radius.

Table 2: Accuracy of the classified point cloud

LAS	NVA (Non-vegetated)	VVA (Vegetated)
RMSEv specification [m]	≤ 0.100	As found
RMSEv calculated values [m]	0.054	0.167
Number of points	42	29
Maximum error [m]	0.088	0.449
Minimum error [m]	-0.153	-0.219
Mean Error [m]	0.001	0.082
Median error [m]	0.005	0.066
Standard deviation [m]	0.045	0.145

Table 3: Accuracy of the Derived DEM

DEM	NVA (Non-vegetated)	VVA (Vegetated)
RMSEv specification [m]	≤ 0.100	As found
RMSEv calculated values [m]	0.054	0.184
Number of points	42	31
Maximum error [m]	0.116	0.459
Minimum error [m]	-0.149	-0.173
Mean Error [m]	0.001	0.102
Median error [m]	-0.001	0.082
Standard deviation [m]	0.046	0.153

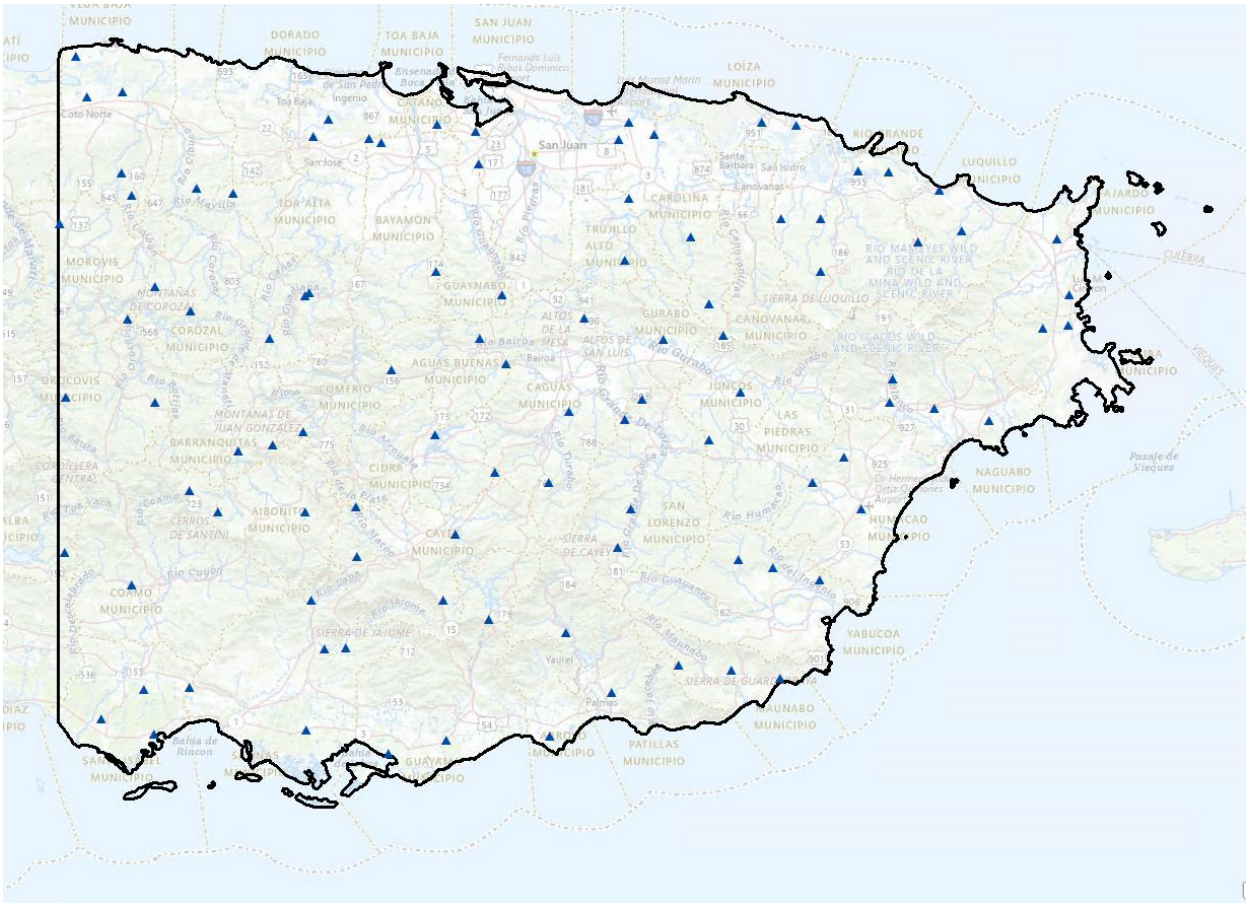


Figure 9: NVA and VVA Checkpoints - Classified Point Cloud & DEM

3.4 Relative Accuracy

3.4.1 Interswath Accuracy Analysis

Swath Separation Imagery was produced for the entire project area. Swath separation images use color-coding to illustrate differences in elevation (z-) values where swaths overlap. The color-coded images are semi-transparent and overlay the lidar intensity image. They are ancillary data used as visual aids to more easily identify regions within point cloud datasets that may have suspect interswath alignment or other geometric issues. Imagery was created using last returns with all classification and bit flags, except for noise and withheld bit flag are included. Images are derived from a TIN. The swath surface elevation is the average elevation of the valid point-in-cell from that swath. The DZ value used for the colorization of each SSI pixel is calculated by subtracting the lowest swath surface elevation from the highest swath surface elevation. These images have a 50% transparent RGB layer over lidar intensity. Color intervals are as follows: 0-8cm, green; 8-16cm, yellow; 16-24cm orange >24cm, red. These files were produced as GeoTIFF

tiles using a cell size of 1 meter. SSI are generated from the point cloud data and will not be altered after creation, nor will there be further maintenance on this product.

An overview can be seen below:

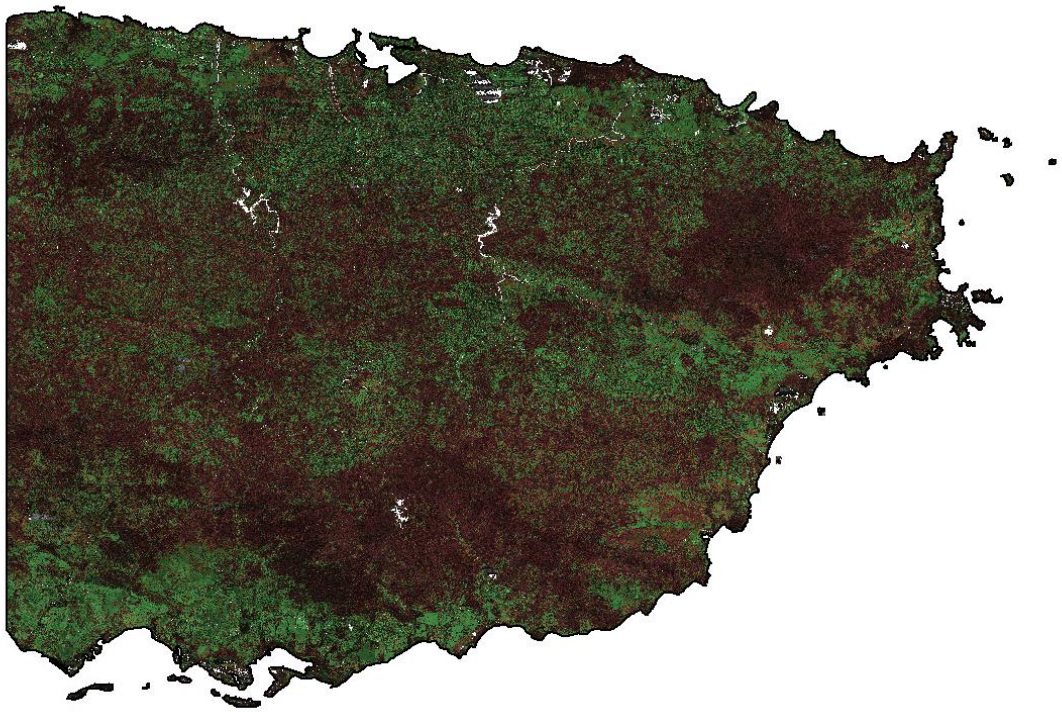


Figure 10: Swath Separation Images

3.4.2 Intraswath Accuracy Analysis

Smooth Surface Repeatability: In ideal theoretical conditions, smooth surface repeatability is a measure of variations documented on a surface that would be expected to be flat and without variation. Users of lidar technology commonly refer to these variations as "noise." Single-swath data was visually assessed using only single returns in non-vegetated areas. Repeatability was visually evaluated by measuring departures from planarity of single returns from hard planar surfaces, normalizing for actual variation in the surface elevation. Repeatability of only single returns was then visually assessed at multiple locations within hard surfaced areas (for example, parking lots or large rooftops).

Each sample area was visually evaluated using a signed difference raster (maximum elevation − minimum elevation) at a cell size equal to twice the ANPS, rounded up to the next integer. Sample areas were larger than 50 square meters (m2). The maximum variations within sample areas for this project was $\leq$6 cm. Isolated noise is expected within the sample areas and was disregarded.