Dewberry

Louisiana Coastal Lidar Project Report

Report Produced for U.S. Geological Survey

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1. EXECUTIVE SUMMARY

The primary purpose of this project was to develop a consistent and accurate surface elevation dataset derived from high-accuracy light detection and ranging (lidar) technology for the USGS Louisiana Coastal project area.

Lidar data were processed and classified according to project specifications. Detailed breaklines and bare-earth Digital Elevation Models were produced for the project area. Project components were formatted based on a tile grid with each tile covering an area 1,000 m by 1,000 m. A total of 8,335 tiles were produced for the project, providing approximately 3,243 sq. miles of coverage.

1.1 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 completed the ground survey for the project and delivered surveyed checkpoints. Ground control points and checkpoints were surveyed for the project. Ground control points were used in calibration activities and checkpoints were used in independent testing of the vertical accuracy of the lidar-derived surface model.

Digital Aerial Solutions (DAS) completed lidar data acquisition and data calibration for the project area.

1.2 Project Area

The project area is shown in figure 1. WUID 228382 contains 2,084 1,000 m by 1,000 m tiles. WUID 197958 contains 6,251 1,000 m by 1,000 m tiles. The project tile grid contains 8,335 1,000 m by 1,000 m tiles.

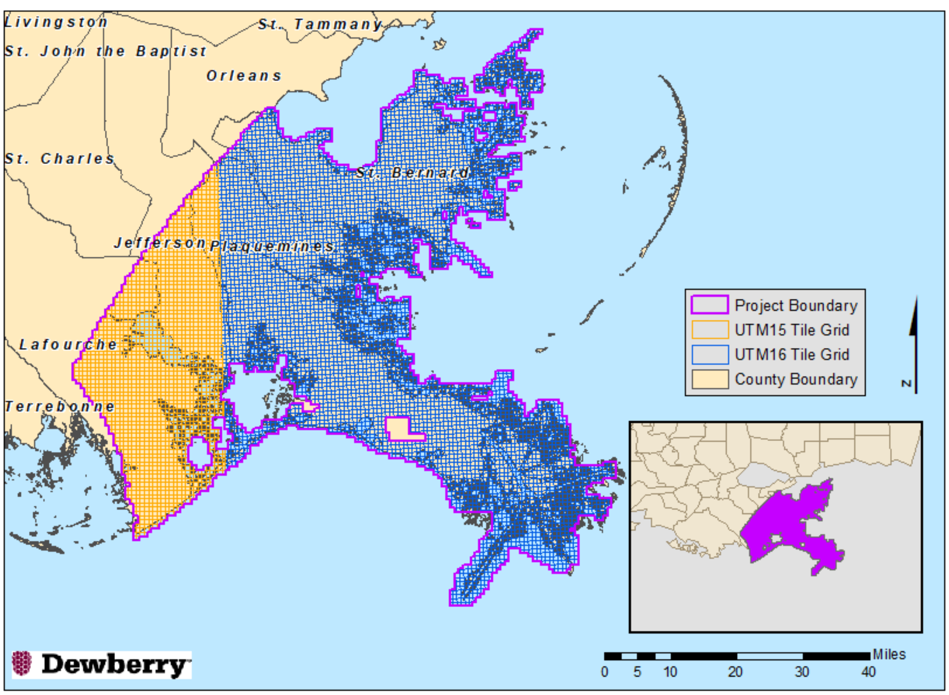


Figure 1. Project map and tile grid.

1.3 Coordinate Reference System

Data produced for the project are delivered in the following spatial reference system:

Horizontal Datum:	North American Datum of 1983 with the 2011 Adjustment (NAD 83 (2011))
Vertical Datum:	North American Vertical Datum of 1988 (NAVD88)
Geoid Model:	Geoid18
Coordinate System:	UTM Zones 15N and 16N
Horizontal Units:	Meters
Vertical Units:	Meters

1.4 Project Deliverables

The deliverables for the project are as follows:

1. Project Extents (Esri SHP)
2. Calibration Points (coordinates, Esri shapefile)
3. Classified Point Cloud (tiled LAS)
4. Independent Survey Checkpoint Data (report, photos, coordinates, Esri shapefiles)
5. Intensity Images (tiled, 8-bit gray scale, GeoTIFF format)
6. Breakline Data (file GDB)
7. Bare Earth Surface (tiled raster DEM, GeoTIFF format)
8. Swath Separation Images
9. Interswath Polygons
10. Intraswath Polygons
11. Metadata (XML)
12. Block Report
13. Flightline Extents GDB
14. Maximum Surface Height Rasters (tiled raster MSHRs, GeoTIFF format)

1.5 Dewberry Production Workflow Diagram

The diagram below outlines Dewberry's standard lidar production workflow.

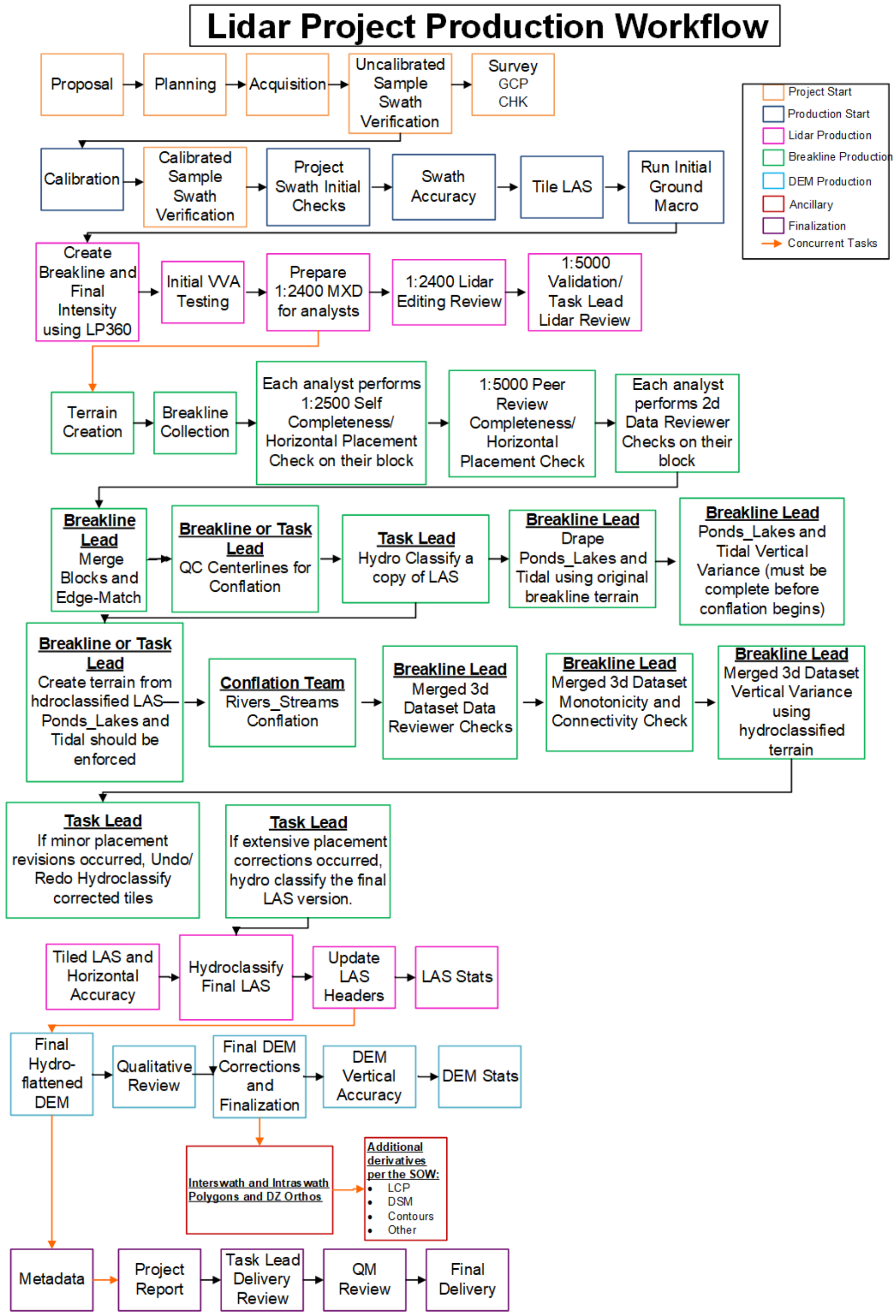


Figure 2. Dewberry's Lidar Production Workflow Diagram

2. LIDAR ACQUISITION REPORT

Dewberry elected to subcontract the lidar acquisition and calibration activities to Digital Aerial Solutions (DAS). DAS was responsible for providing lidar acquisition, calibration, and delivery of lidar data files to Dewberry.

2.1 Acquisition Extents

Figure 3 shows flightline vectors by lift.

Figure 3. Project swaths

2.2 Acquisition Summary

DAS planned 473 passes for the project area as a series of parallel flight lines with cross flightlines for the purposes of quality control. The flight plan included zigzag flight line collection as a result of the inherent IMU drift associated with all IMU systems. In order to reduce any margin for error in the flight plan, DAS followed FEMA's Appendix A "guidelines" for flight planning and, at a minimum, includes the following criteria:

- A digital flight line layout using LEICA MISSION PRO flight design software for direct integration into the aircraft flight navigation system.
- Planned flight lines; flight line numbers; and coverage area.

- Lidar coverage extended by a predetermined margin beyond all project borders to ensure necessary over-edge coverage appropriate for specific task order deliverables.
- Local restrictions related to air space and any controlled areas have been investigated so that required permissions can be obtained in a timely manner with respect to schedule. Additionally, DAS will file our flight plans as required by local Air Traffic Control (ATC) prior to each mission.

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

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

DAS lidar sensors are calibrated at a designated site located at the Plant City Airport in Plant City, Florida and are periodically checked and adjusted to minimize corrections at project sites.

2.3 Sensor Calibration and Boresight

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 Leica CloudPro software (ver 1.2.4). The initial point generation for each mission calibration is verified within Microstation/Terrascan for calibration errors. If a calibration error greater than specification is observed within the mission, the roll, pitch and scanner scale corrections that need to be applied are calculated. The missions with the new calibration values are regenerated and validated internally once again to ensure quality.

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

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

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

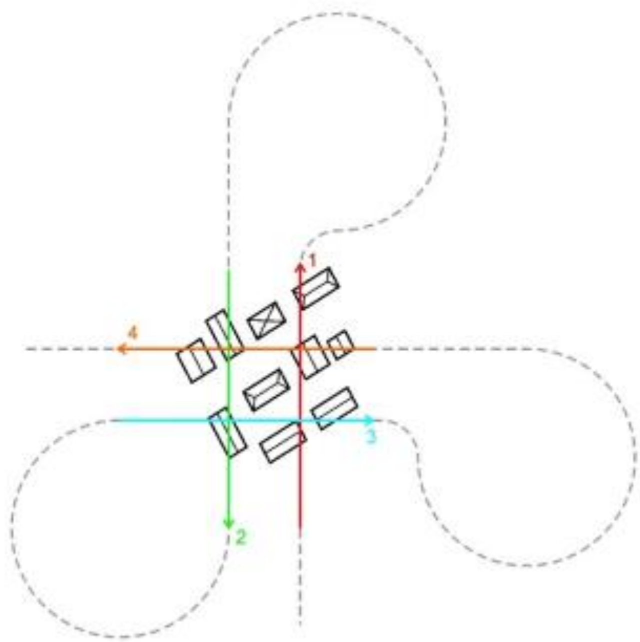


Figure 4. A typical calibration and boresight flight plan where above ground features are acquired from all four cardinal directions, any offsets of the above ground features between overlapping and other directional flight lines is analyzed, and corrections are applied as necessary to ensure proper configuration of the sensor.

2.4 Lidar Acquisition and Processing Details

Table 1 outlines lidar acquisition details, including the project spatial reference system, and processing software used for this project.

Table 1. Lidar acquisition details

Parameter	Value
Number of Flight lines	463
Approximate Area	2,933.47 sq. miles
Acquisition Dates	March 4, 2021 – November 23, 2021
Horizontal Datum	North American Datum of 1983 (NAD83) 2011
Vertical Datum	North American Vertical Datum of 1988 (NAVD88)
Geoid Model	Geoid18
Coordinate Reference System	UTM Zone 15N
Horizontal Units	Meters
Vertical Units	Meters
Kinematic Solution Processing Software:	Inertial Explorer (ver 8.9)
Point Cloud Generation Software	Lecia CloudPro software (ver 1.2.4)
Calibration Software	BayesMap StripAlign

2.5 Lidar System parameters

Digital Aerial Solutions operated a Cessna421 (Tail # N112MJ) outfitted with a LEICA ALS80-HP SN#8235 lidar system during the collection of the Coastal Louisiana study area. Table 2 details the lidar system parameters used during acquisition for this project.

Table 2. Digital Aerial Solutions lidar system parameters.

Parameter	Value
System	Leica ALS80_HP SN#8235
Altitude (m above ground level)	1277
Nominal flight speed (kts)	155
Scanner pulse rate (kHz)	642.8
Scan frequency (Hz)	58.4
Pulse duration of the scanner (ns)	3
Pulse width of the scanner (m)	0.31
Central wavelength of the sensor laser (nm)	1064
Multiple pulses in the air	Yes
Beam divergence (mrad)	0.15
Nominal swath width on the ground (m)	684.61
Swath overlap (%)	30
Total sensor scan angle (degrees)	30
Computed down track spacing per beam (m)	0.12
Computed cross track Spacing per beam (m)	0.13
Nominal pulse spacing (NPS) (single swath) (m)	0.29
Nominal Pulse Density (NPD) (single swath) (points per sq m)	8
Aggregate NPS (m) (if NPS was designed to be met through single coverage, ANPS and NPS will be equal)	0.29
Aggregate NPD (m) (if NPD was designed to be met through single coverage, ANPD and NPD will be equal)	8
Maximum Number of Returns per Pulse	642,800 Hz

2.6 Acquisition Static Control

Digital Aerial Solutions deployed static GPS base stations during the acquisition of the Louisiana Coastal Lidar Project. Locations were chosen based on ease of access and clear line of sight to the satellite constellation. Location data was recorded at a frequency of 1 Hz to ensure the highest quality positional solution. Static base station data was incorporated during the kinematic post-processing of aircraft position.

Base stations were set on existing monuments where available. If no existing monuments were convenient for base station setup, new benchmarks were established. The coordinates of these base stations are provided in the table below.

Table 3. Base stations used to control lidar acquisition.

Name	NAD83(2011) UTM Zone 15, m		NAD83(2011), m	NAVD88 Geoid18, m
	Easting (X)	Northing (Y)	Ellipsoid Height	Orthometric Height
GA01	765377.356	3260127.214	-24.416	0.174
GA02	765375.986	3260143.541	-24.389	0.201
MSIN	826572.713	3358215.493	-17.322	9.640

2.7 ABGNSS-Inertial Processing

ABGNSS-Inertial processing was performed using the software identified in Table 1. The reference frame used for this processing does not always match the project spatial reference system and is shown in Table 4.

Appendix A contains additional mission GPS and IMU processing covering:

- Inertial Explorer version 8.9 graphics and processing
- Graphics of any reference stations used for differential correction
- Graphics of processing interface to show trajectory data and labeled reference stations for each lift (only graphics of trajectory when precise point position is used).
- Graphics of processed plots for each mission/flight/lift to include:
    1. Forward/reverse separation of trajectory
    2. Estimated accuracy of trajectory
    3. Any additional plots used in the analyses of trajectory quality

Table 4. Spatial reference system used for ABGNSS-Inertial processing

Parameter	Value
Horizontal Datum	North American Datum of 1983 (NAD83)
Vertical Datum	North American Vertical Datum of 1988 (NAVD88)
Geoid Model	Geoid18
Coordinate Reference System	UTM Zone 15N
Horizontal Units	Meters
Vertical Units	Meters

2.8 Final Calibration Verification

Dewberry surveyed 51 ground control points (GCPs) in flat, non-vegetated areas to test the accuracy of the calibrated swath data. GCPs were located in open, non-vegetated terrain. To assess the accuracy of calibration, the heights of the ground control points were compared with a surface derived from the calibrated swath lidar. A full list of GCPs used for accuracy testing is included in the GCP Survey Report provided with project deliverables. All GCPs were tested against UTM 15 data before WUID 197958 was projected in UTM 16.

Table 5. Summary of calibrated swath vertical accuracy tested with ground control points.

Land Cover Type	# of Points	$RMSE_z$ (m)	NVA (m)	Mean (m)	Median (m)	Skew	Std Dev (m)	Min (m)	Max (m)	Kurtosis
Ground Control Points (GCPs)	51	0.074	0.144	0.019	0.015	-0.743	0.072	-0.275	0.253	6.452

3. LIDAR PROCESSING & QUALITATIVE ASSESSMENT

3.1 Initial Processing

Dewberry performed vertical accuracy validation of the swath data, inter-swath relative accuracy validation, intra-swath relative accuracy validation, verification of horizontal alignment between swaths, and confirmation of point density and spatial distribution. This initial assessment allowed Dewberry to determine whether the data was suitable for full-scale production.

3.1.1 Post Calibration Lidar Review

The table below identifies requirements verified by Dewberry prior to tiling the swath data, running initial ground macros, and starting manual classification.

Table 6. Post calibration and initial processing data verification steps.

Requirement	Description of Deliverables	Additional Comments
Non-vegetated vertical accuracy (NVA) of the swath data meet required specifications of 19.6 cm at the 95% confidence level based on RMSEz (10 cm) x 1.96	The swath NVA was tested and passed specifications.	None
The NPD/NPS (or Aggregate NPD/Aggregate NPS) meets required specification of 8 ppsm or 0.35 m NPS. The NPD (ANPD) is calculated from first return points only.	The average calculated (A)NPD of this project is 8.5 ppsm. Density raster visualization also passed specifications.	None
Spatial Distribution requires 90% of the project grid, calculated with cell sizes of 2*NPS, to contain at least one lidar	94.6% of cells (2*NPS cell size) had at least 1 lidar point within the cell.	None

Requirement	Description of Deliverables	Additional Comments
point. This is calculated from first return points only.		
Within swath (Intra-swath or hard surface repeatability) relative accuracy must meet ≤ 6 cm maximum difference	Within swath relative accuracy passed specification.	None
Between swath (Inter-swath or swath overlap) relative accuracy must meet 8 cm RMSDz/16 cm maximum difference. These thresholds are tested in open, flat terrain.	Between swath relative accuracy passed specification, calculated from single return lidar points.	None
Horizontal Calibration-There should not be horizontal offsets (or vertical offsets) between overlapping swaths that would negatively impact the accuracy of the data or the overall usability of the data. Assessments made on rooftops or other hard planar surfaces where available.	Horizontal calibration met project requirements.	None
Ground Penetration-The missions were planned appropriately to meet project density requirements and achieve as much ground penetration beneath vegetation as possible	Ground penetration beneath vegetation was acceptable.	None
Sensor Anomalies-The sensor should perform as expected without anomalies that negatively impact the usability of the data, including issues such as excessive sensor noise and intensity gain or range-walk issues	No sensor anomalies were present.	None
Edge of Flight line bits-These fields must show a minimum value of 0 and maximum value of 1 for each swath acquired, regardless of which type of sensor is used	Edge of Flight line bits were populated correctly	None
Scan Direction bits-These fields must show a minimum value of 0 and maximum value of 1 for each swath acquired with sensors using oscillating (back-and-forth) mirror scan mechanism. These fields should show a minimum and maximum of 0 for each swath acquired with Riegl sensors as these sensors use rotating mirrors.	Scan Direction bits were populated correctly	None
Swaths are in LAS v1.4 formatting	Swaths were in LAS v1.4 as required by the project.	None

Requirement	Description of Deliverables	Additional Comments
All swaths must have File Source IDs assigned (these should equal the Point Source ID or the flight line number)	File Source IDs were correctly assigned	None
GPS timestamps must be in Adjusted GPS time format and Global Encoding field must also indicate Adjusted GPS timestamps	GPS timestamps were Adjusted GPS time and Global Encoding field were correctly set to 17	None
Intensity values must be 16-bit, with values ranging between 0-65,535	Intensity values were 16-bit	None
Point Source IDs must be populated and swath Point Source IDs should match the File Source IDs	Point Source IDs were assigned and match the File Source IDs	None

3.2 Data Classification and Editing

Once the calibration, absolute swath vertical accuracy, and relative accuracy of the data were confirmed, Dewberry utilized proprietary and TerraScan software for processing. The acquired 3D laser point clouds were tiled according to the project tile grid using proprietary software. Once tiled, the laser points were classified using a proprietary routine in TerraScan. This routine classified any obvious low outliers in the dataset to class 7 and high outliers in the dataset to class 18. Points along flight line edges that may be geometrically unusable were flagged as withheld and classified to a separate class so that they would be excluded from the initial ground algorithm. After points that could negatively affect the ground were removed from class 1, the ground layer was extracted from this remaining point cloud using an iterative surface model.

This surface model was generated using four main parameters: building size, iteration angle, iteration distance, and maximum terrain angle. The initial model was based on low points being selected by a "roaming window" with the assumption that these were the ground points. The size of this roaming window was determined by the building size parameter. The low points were triangulated and the remaining points were evaluated and subsequently added to the model if they met the iteration angle and distance constraints. This process was repeated until no additional points were added within iterations. Points that did not relate to classified ground within the maximum terrain angle were not captured by the initial model.

After the initial automated ground routine, each tile was imported into TerraScan and a surface model was created to examine the ground classification. Dewberry analysts visually reviewed the ground surface model and corrected errors in the ground classification such as vegetation, buildings, and bridges that were present following the initial processing. Dewberry analysts employed 3D visualization techniques to view the point cloud at multiple angles and in profile to ensure that non-ground points were removed from the ground classification. Bridge decks were classified to class 17 and bridge saddle breaklines were used where necessary. After the ground classification corrections were completed, the dataset was processed through a water classification routine that utilized breaklines to automatically classify hydro features. The water classification routine selected ground points within the breakline polygons and automatically classified them as class 9, water. During this water classification routine, points that were within 1 NPS distance or less of the hydrographic feature boundaries were moved to class 20, ignored ground, to avoid hydro-flattening artifacts along the edges of hydro features.

The withheld bit was set on the withheld points previously identified in TerraScan before the ground classification routine was performed. The withheld bit was set on points classified as noise (classes 7 and 18) after manual clean-up.

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

3.2.1 Qualitative Review

Dewberry's qualitative assessment of lidar point cloud data utilized a combination of statistical analyses and visual interpretation. Methods and products used in the assessment included profile- and map view-based point cloud review, pseudo image products (e.g., intensity orthoimages), TINs, DEMs, DSMs, and point density rasters. This assessment looked for incorrect classification and other errors sourced in the LAS data. Lidar data are peer reviewed, reviewed by task leads (senior level analysts), and verified by an independent QA/QC team at key points within the lidar workflow.

The following table describes Dewberry's standard editing and review guidelines for specific types of features, land covers, and lidar characteristics.

Table 7. Lidar editing and review guidelines.

Category	Editing Guideline	Additional Comments
No Data Voids	The SOW for the project defines unacceptable data voids as voids greater than 4 x ANPS^2, or 1.96 m^2, that are not related to water bodies or other areas of low near-infrared reflectivity and are not appropriately filled by data from an adjacent swath. The LAS files were used to produce density grids based on Class 2 (ground) points for review.	No unacceptable voids were identified in this dataset
Artifacts	Artifacts in the point cloud are typically caused by misclassification of points in vegetation or man-made structures as ground. Low-lying vegetation and buildings are difficult for automated grounding algorithms to differentiate and often must be manually removed from the ground class. Dewberry identified these features during lidar editing and reclassified them to Class 1 (unassigned). Artifacts up to 0.3 m above the true ground surface may have been left as Class 2 because they	None

Category	Editing Guideline	Additional Comments
	do not negatively impact the usability of the dataset.	
Bridge Saddles	The DEM surface models are created from TINs or terrains. TIN and terrain models create continuous surfaces from the input points, interpolating surfaces beneath bridges where no lidar data was acquired. The surface model in these areas tend to be less detailed. Bridge saddles may be created where the surface interpolates between high and low ground points. Dewberry identifies problems arising from bridge removal and resolves them by reclassifying misclassified ground points to class 1 and/or adding bridge saddle breaklines where applicable due to interpolation.	None
Culverts and Bridges	It is Dewberry's standard operating procedure to leave culverts in the bare earth surface model and remove bridges from the model. In instances where it is difficult to determine whether the feature was a culvert or bridge, Dewberry errs on the side of culverts, especially if the feature is on a secondary or tertiary road.	None
In-Ground Structures	In-ground structures typically occur on military bases and at facilities designed for munitions testing and storage. When present, Dewberry identifies these structures in the project and includes them in the ground classification.	No in-ground structures present in this dataset
Dirt Mounds	Irregularities in the natural ground, including dirt piles and boulders, are common and may be misinterpreted as artifacts that should be removed. To verify their inclusion in the ground class, Dewberry checked the features for any points above or below the surface that might indicate vegetation or lidar penetration and reviews ancillary layers in these locations as well. Whenever determined to be natural or ground	No dirt mounds or other irregularities in the natural ground were present in this dataset

Category	Editing Guideline	Additional Comments
	features, Dewberry edits the features to class 2 (ground)	
Irrigated Agricultural Areas	Per project specifications, Dewberry collected all areas of standing water greater than or equal to 2 acres, including areas of standing water within agricultural areas and not within wetland or defined waterbody, hydrographic, or tidal boundaries. Areas of standing water that did not meet the 2 acre size criteria were not collected.	Standing water within agricultural areas not present in the data
Wetland/Marsh Areas	Vegetated areas within wetlands/marsh areas are not considered water bodies and are not hydroflattened in the final DEMs. However, it is sometimes difficult to determine true ground in low wet areas due to low reflectivity. In these areas, the lowest points available are used to represent ground, resulting in a sparse and variable ground surface. Open water within wetland/marsh areas greater than or equal to 2 acres is collected as a waterbody.	Marshes present in the data
Flight Line Ridges	Flight line ridges occur when there is a difference in elevation between adjacent flight lines or swaths. If ridges are visible in the final DEMs, Dewberry ensures that any ridges remaining after editing and QA/QC are within project relative accuracy specifications.	No flight line ridges are present in the data
Temporal Changes	If temporal differences are present in the dataset, the offsets are identified with a shapefile.	Temporal polygons provided to delineate temporal offsets
Low NIR Reflectivity	Some materials, such as asphalt, tars, and other petroleum-based products, have low NIR reflectivity. Large-scale applications of these products, including roadways and roofing, may have diminished to absent lidar returns. USGS LBS allow for this characteristic of lidar but if low NIR reflectivity is causing voids in the final bare earth surface, these locations are identified with a shapefile.	No Low NIR Reflectivity is present in the data

Category	Editing Guideline	Additional Comments
Laser Shadowing	Shadows in the LAS can be caused when solid features like trees or buildings obstruct the lidar pulse, preventing data collection on one or more sides of these features. First return data is typically collected on the side of the feature facing toward the incident angle of transmission (toward the sensor), while the opposite side is not collected because the feature itself blocks the incoming laser pulses. Laser shadowing typically occurs in areas of single swath coverage because data is only collected from one direction. It can be more pronounced at the outer edges of the single coverage area where higher scanning angles correspond to more area obstructed by features. Building shadow in particular can be more pronounced in urban areas where structures are taller. Data are edited to the fullest extent possible within the point cloud. As long as data meet other project requirements (density, spatial distribution, etc.), no additional action taken.	No Laser Shadowing is present in the data

3.2.2 Formatting Review

After the final QA/QC was performed and all corrections were applied to the dataset, all lidar files were updated to the final format requirements and the final formatting, header information, point data records, and variable length records were verified using proprietary tools. The table below lists the primary lidar header fields that are updated and verified.

Table 8. Classified lidar formatting parameters

Parameter	Project Specification	Pass/Fail
LAS Version	1.4	Pass
Point Data Record Format	6	Pass
Horizontal Coordinate Reference System	NAD83 (2011) UTM Zones 15N and 16N, meters in WKT format	Pass
Vertical Coordinate Reference System	NAVD88 (Geoid 18), meters in WKT format	Pass
Global Encoder Bit	17 for adjusted GPS time	Pass

Parameter	Project Specification	Pass/Fail
Time Stamp	Adjusted GPS time (unique timestamps)	Pass
System ID	Sensor used to acquire data	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 recorded for each pulse	Pass
Classification	Class 1: Unclassified Class 2: Ground Class 7: Low Noise Class 9: Water Class 17: Bridge Decks Class 18: High Noise Class 20: Ignored Ground Class 32: Levee	Pass
Withheld Points	Withheld bits set for geometrically unreliable points and for noise points in classes 7 and 18	Pass
Scan Angle	Recorded for each pulse	Pass
XYZ Coordinates	Recorded for each pulse	Pass

4. LIDAR POSITIONAL ACCURACY

4.1 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 (see sections 6.1 and 6.2). 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. For accuracy testing, Dewberry typically uses proprietary software, which utilizes both Esri and lastools software within its workflow, to test the swath lidar vertical accuracy and classified lidar vertical accuracy.

Dewberry tested the horizontal accuracy of lidar datasets when checkpoints were photo-identifiable in the intensity imagery. Photo-identifiable checkpoints included 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 viewed in the intensity imagery were compared to surveyed XY coordinates for each photo-identifiable checkpoint. The horizontal differences were used to compute the tested horizontal accuracy of the lidar.

4.2 Surveyed Vertical Accuracy Checkpoints

The Louisiana Coastal lidar project encompasses approximately 3,243 square miles within the state of Louisiana, covering two different UTM zones. The figure below shows the two UTM zones for the Louisiana Coastal project and the checkpoints that were collected. A complete list of survey checkpoints is contained in the project survey report, which is included as a project deliverable. All checkpoints were tested against UTM 15 data before WUID 197958 was projected in UTM 16.

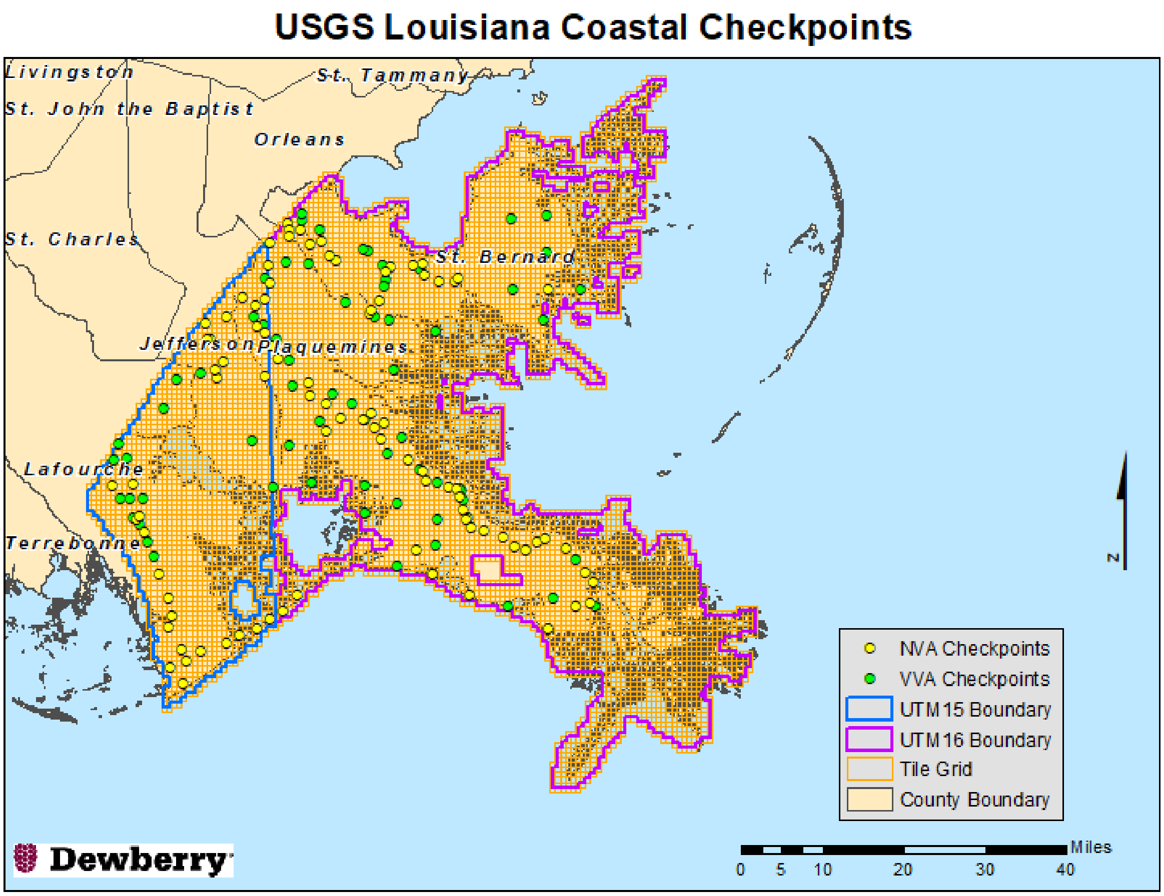


Figure 5. Project map with UTM zones outlined and checkpoints in each UTM zone displayed.

4.3 Vertical Accuracy Test Procedures

NVA (Non-vegetated Vertical Accuracy) reflects the calibration and performance of the lidar sensor. NVA was determined with checkpoints located only in non-vegetated terrain, including open terrain (grass, dirt, sand, and/or rocks) and urban areas. In these locations it is likely that the lidar sensor detected the bare-earth ground surface and random errors are expected to follow a normal error distribution. Assuming 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.

VVA (Vegetated Vertical Accuracy) was determined with all checkpoints in vegetated land cover categories, including tall grass, weeds, crops, brush and low trees, and fully forested areas. In these locations 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 VVA is accompanied by a listing of the 5% outliers that are larger than the 95th percentile used to compute the VVA.

The relevant testing criteria are summarized in the table below.

Table 9. Vertical accuracy acceptance criteria

Land Cover Type	Quantitative Criteria	Measure of Acceptability
NVA	Accuracy in open terrain and urban land cover categories using RMSEz *1.9600	19.6 cm ($RMSE_z$ 10 cm)
VVA	Accuracy in vegetated land cover categories combined at the 95th percentile	30 cm

4.4 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 non-vegetated (open terrain and urban) independent survey checkpoints. 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. The table below summarizes the swath project accuracy specification, the amount of NVA points tested, and the final tested swath accuracy results.

Table 10. Tested NVA and descriptive statistics from unclassified lidar swaths

100 % of Totals	# of Points	RMSEz (m) NVA	NVA (m) Spec=0.196	Mean (m)	Median (m)	Skew	Std Dev (m)	Kurtosis	Min (m)	Max (m)
NVA	93	0.071	0.140	0.018	0.030	-0.701	0.069	-0.191	0.139	0.389

Three checkpoints (NVA_138, NVA_139, NVAH_017) were removed from the raw swath vertical accuracy testing due to their location on unsuitable surfaces. Table 11, below, provides the coordinates for these checkpoints and the vertical accuracy results from the unclassified swath data. Figures 6, 7, and 8 below, show the three checkpoints removed from swath vertical accuracy testing.

Table 11. Checkpoints removed from unclassified swath vertical accuracy testing

Point ID	UTM Zone 15N NAD83(2011), m		NAVD88 Geoid 18, m		Delta Z (m)
	Easting X (m)	Northing Y (m)	Survey Z (m)	Lidar Z (m)	
NVA_138	784564.830	3276167.065	0.966	0.798	-0.168
NVA_139	795208.334	3276848.101	0.335	0.434	0.099
NVAH_017	803515.822	3308673.683	0.624	0.636	0.012

Figure 6. Checkpoint NVA_138. This checkpoint is located on a concrete dock. Review by Dewberry deemed this survey checkpoint unsuitable to use in the swath vertical accuracy testing.

Figure 7. Checkpoint NVA_139. This checkpoint is submerged. Review by Dewberry deemed this survey checkpoint unsuitable to use in the swath vertical accuracy testing.

Figure 8. Checkpoint NVAH_017. This checkpoint is located on buried concrete. Review by Dewberry deemed this survey checkpoint unsuitable to use in the swath vertical accuracy testing.

4.5 Classified Lidar Vertical Accuracy Results

The table below 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.

Table 12. Tested NVA and VVA for the classified lidar

Land Cover Type	# of Points	NVA (m)	VVA (m)
Project Specification	**155**	**0.196**	**0.300**
NVA	93	0.141	-
VVA	65	-	0.289

Four checkpoints (NVA_138, NVA_139, NVAH_017, and VVA_079) were removed from the classified lidar vertical accuracy testing due to their location on unsuitable surfaces. Table 13, below, provides the coordinates for these checkpoints and the vertical accuracy results from the unclassified swath data. Figure 9 below shows VVA_079 removed from the classified lidar vertical accuracy testing.

Table 13. Checkpoints omitted from classified lidar vertical accuracy testing

Point ID	UTM Zone 15N NAD83(2011), m		NAVD88 Geoid 18, m		Delta Z (m)
	Easting (X)	Northing (Y)	Survey Z	Lidar Z	
NVA_138	784564.830	3276167.065	0.966	-0.6	1.566
NVA_139	795208.334	3276848.101	0.335	0.454	0.119
NVAH_017	803515.822	3308673.683	0.624	0.621	-0.003
VVA_079	827099.933	3250879.552	0.458	-0.6	-1.058

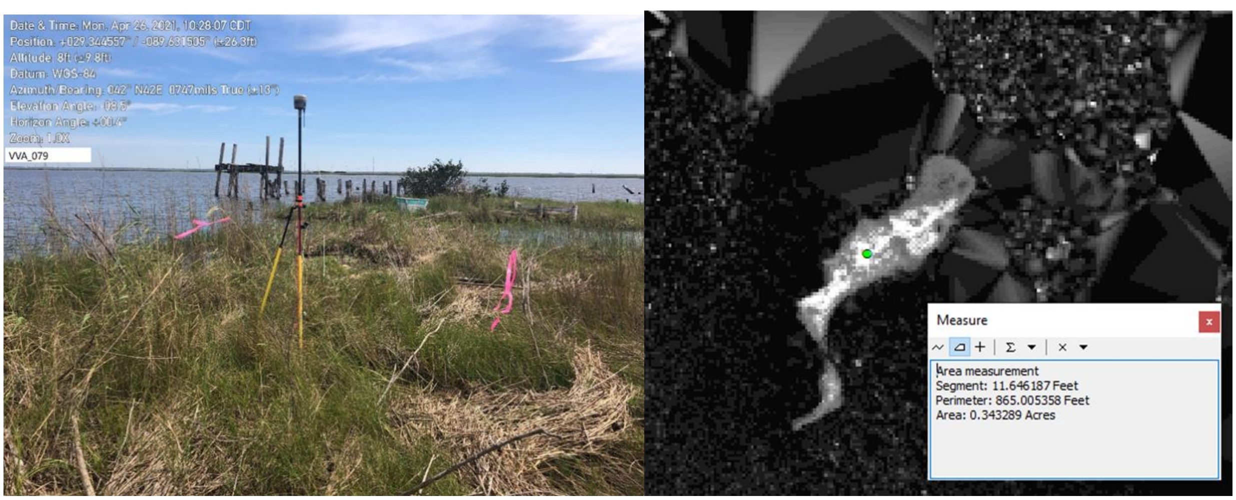


Figure 9. Checkpoint VVA_079. This checkpoint is located on an ungrounded island below the breakline collection specification. Review by Dewberry deemed this survey checkpoint unsuitable to use in the classified lidar vertical accuracy testing.

This classified lidar dataset was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 10 cm $RMSE_z$ vertical accuracy class. Actual NVA accuracy was found to be $RMSE_z$ = 7.2 cm, equating to ± 7.2 cm at 95% confidence level. Actual VVA accuracy was found to be ± 28.9 cm at the 95th percentile. The 5% outliers are listed in Table 13. Descriptive statistics for both sets of checkpoints are presented in Table 14.

Table 14. VVA 5% outliers

Point ID	UTM Zone 15N NAD83(2011), m		NAVD88 Geoid 12B, m		Delta Z (m)
	Easting X (m)	Northing Y (m)	Survey Z (m)	Lidar Z (m)	
VVA_061	823639.362	3256082.984	0.258	0.550	0.292
VVA_067	854813.387	3238909.738	0.635	1.140	0.505
VVA_072	844625.421	3295616.480	0.184	0.530	0.346
VVA_022	809050.379	3309608.826	-0.740	-0.350	0.390

Table 15. Classified lidar vertical accuracy descriptive statistics

Land Cover Type	# of Points	$RMSE_z$ (m)	Mean (m)	Median (m)	Skew	Std Dev (m)	Min (m)	Max (m)	Kurtosis
NVA	93	0.072	0.018	0.030	-0.720	0.070	-0.195	0.139	0.437
VVA	65	-	0.072	0.066	0.890	0.122	-0.158	0.505	2.106

Based on the vertical accuracy testing conducted by Dewberry, the lidar dataset for the USGS Louisiana Coastal Lidar Project satisfies the vertical accuracy requirements.

4.6 Horizontal Accuracy Test Procedures

Horizontal accuracy testing requires well-defined checkpoints that can be visually identified in the dataset. Elevation datasets, including lidar datasets, do not always contain well-defined checkpoints suitable for horizontal accuracy assessment. Dewberry reviewed all NVA checkpoints to determine which, if any, of these checkpoints were located on photo-identifiable features in the intensity imagery. This subset of checkpoints was used for horizontal accuracy testing.

The horizontal accuracy testing steps used by Dewberry are summarized as follows:

1. Dewberry's team surveyed X, Y, and Z coordinates for discrete checkpoints in accordance with project specifications. Dewberry targeted half of the NVA checkpoints for location on features that would photo-identifiable in the intensity imagery.
2. Following initial processing, Dewberry located the photo-identifiable features in the intensity imagery, utilizing Esri software.
3. Dewberry computed the differences in X and Y values between the surveyed coordinates and the lidar coordinates of the photo-identifiable feature.
4. Horizontal accuracy was assessed based on these data using NSSDA methodology where horizontal accuracy is calculated at the 95% confidence level. The results are provided in the following section.

4.7 Horizontal Accuracy Results

Fifteen checkpoints were determined to be photo-identifiable in the intensity imagery and were used to test the horizontal accuracy of the lidar dataset. Due to the small number of available checkpoints, the results reported herein are not considered statistically significant. The results are detailed below and listed in Table 15.

Using NSSDA methodology (endorsed by the ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014)), horizontal accuracy at the 95% confidence level (called $Accuracy_r$) is computed by the formula $RMSE_r * 1.7308$ or $RMSE_{xy} * 2.448$.

No horizontal accuracy requirements or thresholds were provided for this project. However, this data set was produced to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 41 cm $RMSE_x$/$RMSE_y$ horizontal accuracy class which equates to a positional horizontal accuracy = ± 1 meter at the 95% confidence level. Using this small sample of 15 photo-identifiable checkpoints, positional accuracy of this dataset was found to be $RMSE_x$ = 27.8 cm and $RMSE_y$ = 25.6 cm, which equates to ± 65.4 cm at the 95% confidence level.

Table 16. Horizontal accuracy of the classified lidar data at the 95% confidence level

Land Cover Type	# of Points	$RMSE_x$ (m)	$RMSE_y$ (m)	$RMSE_r$ (m)	$Accuracy_r$ (m)
Project Target	**-**	**0.410**	**0.410**	**0.580**	**1.000**
Non-Vegetated Terrain	15	0.278	0.256	0.378	0.654

5. BREAKLINE PROCESSING & QUALITATIVE ASSESSMENT

4.1 Breakline Production Methodology

Dewberry used intensity imagery, terrain morphology, and other aspects of the lidar point cloud to create a composite image. Manually digitized breaklines from two spatially non-contiguous test areas were used in conjunction with the composite image to train a deep learning model. The trained deep learning model performed image segmentation, classifying pixels in an image scene as either “Water” or “Land”. The output of the model is a binary raster, with one value representing the predicted water features. The raster was converted to vector format as polygons. Filtering was then performed on the polygons to remove small water features and gaps within water features. The filtered predictions were visually reviewed and edited as necessary, within an Esri software environment.

Breakline features with static or semi-static elevations (ponds and lakes, bridge saddles, and soft feature breaklines) were converted to 3D breaklines within the Esri environment where breaklines were draped on terrains or the lidar point cloud. Subsequent processing was done on ponds/lakes to identify the minimum z-values within these features and re-applied that minimum elevation to all vertices of the breakline feature.

Linear hydrographic features show downhill flow and maintain monotonicity. These breaklines underwent conflation by using a combination of Esri and LP360 software. Centerlines were draped on terrains, enforced for monotonicity, and those elevations were then assigned to the bank lines for the final river/stream z-values.

Tidal breaklines may have been converted to 3D using either method, dependent on the variables within each dataset.

4.1.1 Breakline Collection Requirements

The table below outlines breakline collection requirements for this dataset.

Table 17. Breakline collection requirements

Parameter	Project Specification	Additional Comments
Ponds and Lakes	Breaklines are collected in all inland ponds and lakes ~2 acres or greater. These features are flat and level water bodies at a single elevation for each vertex along the bank.	None
Rivers and Streams	Breaklines are collected for all streams and rivers ~100' nominal width or wider. These features are flat and level bank to bank, gradient will follow the surrounding terrain and the water surface will be at or below the surrounding terrain. Streams/river channels will break at culvert locations however not at elevated bridge locations.	None
Tidal	Breaklines are collected as polygon features depicting water bodies such as oceans, seas, gulfs, bays, inlets, salt marshes, very large lakes, etc. Includes any significant water body that is affected by tidal variations. Tidal variations over the course of collection, and between different collections, can result in discontinuities along shorelines. This is considered normal and should be retained. Variations in water surface elevation resulting from tidal variations during collection should not be removed or adjusted. Features should be captured as a dual line with one line on each bank. Each vertex placed shall maintain vertical integrity. Parallel points on opposite banks of the tidal waters must be captured at the same elevation to ensure flatness of the water feature. The entire water	None

Parameter	Project Specification	Additional Comments
	surface edge is at or below the immediate surrounding terrain.	
Islands	Donuts will exist where there are islands greater than 1 acre in size within a hydro feature.	None
Bridge Saddle Breaklines	Bridge Saddle Breaklines are collected where bridge abutments were interpolated after bridge removal causing saddle artifacts.	None
Soft Features	Soft Feature Breaklines are collected where additional enforcement of the modeled bare earth terrain was required, typically on hydrographic control structures or vertical waterfalls, due to large vertical elevation differences within a short linear distance on a hydrographic features.	None

4.2 Breakline Qualitative Assessment

Dewberry performed both manual and automated checks on the collected breaklines. Breaklines underwent peer reviews, breakline lead reviews (senior level analysts), and final reviews by an independent QA/QC team. The table below outlines high level steps verified for every breakline dataset.

Table 18. Breakline verification steps.

Parameter	Requirement	Pass/Fail
Collection	Collect breaklines according to project specifications using lidar-derived data, including intensity imagery, bare earth ground models, density models, slope models, and terrains.	Pass
Placement	Place the breakline inside or seaward of the shoreline by 1-2 x NPS in areas of heavy vegetation or where the exact shoreline is hard to delineate.	Pass
Completeness	Perform a completeness check, breakline variance check, and all automated checks on each block before designating that block complete.	Pass
Merged Dataset	Merge completed production blocks. Ensure correct horizontal and vertical snapping between all production blocks. Confirm correct horizontal placement of breaklines.	Pass

Parameter	Requirement	Pass/Fail
Merged Dataset Completeness Check	Check entire dataset for features that were not captured but that meet baseline specifications or other metrics for capture. Features should be collected consistently across tile boundaries.	Pass
Edge Match	Ensure breaklines are correctly edge-matched to adjoining datasets. Check completion type, attribute coding, and horizontal placement.	Pass
Vertical Consistency	Waterbodies shall maintain a constant elevation at all vertices Vertices should not have excessive min or max z-values when compared to adjacent vertices Intersecting features should maintain connectivity in X, Y, Z planes Dual line streams shall have the same elevation at any given cross-section of the stream	Pass
Vertical Variance	Using a terrain created from lidar ground (class 2, 8, and 20 as applicable) and water points (class 9) to compare breakline Z values to interpolated lidar elevations to ensure there are no unacceptable discrepancies.	Pass
Monotonicity	Dual line streams generally maintain a consistent down-hill flow and collected in the direction of flow – some natural exceptions are allowed	Pass
Topology	Features must not overlap or have gaps Features must not have unnecessary dangles or boundaries	Pass
Hydro-classification	The water classification routine selected ground points within the breakline polygons and automatically classified them as class 9, water. During this water classification routine, points that were within 1 NPS distance or less of the hydrographic feature boundaries were moved to class 20, ignored ground, to avoid hydroflattening artifacts along the edges of hydro features.	Pass
Hydro-flattening	Perform hydro-flattening and hydro-enforcement checks. Tidal waters should preserve as much ground as possible and can be non-monotonic.	Pass

6. DEM PROCESSING & QUALITATIVE ASSESSMENT

5.1 DEM Production Methodology

Dewberry utilized LP360 to generate DEM products and both ArcGIS and Global Mapper for QA/QC.

The final classified lidar points in all bare earth classes were loaded into LP360 along with the final 3D breaklines and the project tile grid. A raster was generated from the lidar data with breaklines enforced and clipped to the project tile grid. The DEM was reviewed for any issues requiring corrections, including remaining lidar misclassifications, erroneous breakline elevations, incorrect or incomplete hydro-flattening or hydro-enforcement, and processing artifacts. The formatting of the DEM tiles was verified before the tiles were loaded into Global Mapper to ensure that there was no missing or corrupt data and that the DEMs matched seamlessly across tile boundaries. A final qualitative review was then conducted by an independent review department within Dewberry.

5.2 DEM Qualitative Assessment

Dewberry performed a comprehensive qualitative assessment of the bare earth DEM deliverables to ensure that all tiled DEM products were delivered with the proper extents, were free of processing artifacts, and contained the proper referencing information. Dewberry conducted the review in ArcGIS using a hillshade model of the full dataset with a partially transparent colorized elevation model overlaid. The tiled DEMs were reviewed at a scale of 1:5,000 to look for artifacts caused by the DEM generation process and to verify correct and complete hydro-flattening and hydro-enforcement. Upon correction of any outstanding issues, the DEM data was loaded into Global Mapper for its second review and to verify corrections.

The table below outlines high level steps verified for every DEM dataset.

Table 19. DEM verification steps.

Parameter	Requirement	Pass/Fail
Digital Elevation Model (DEM) of bare-earth w/ breaklines	DEM of bare-earth terrain surface (1m) is created from lidar ground points and breaklines. DEMs are tiled without overlaps or gaps, show no edge artifact or mismatch, DEM deliverables are .tif format	Pass
DEM Compression	DEMs are not compressed	Pass
DEM NoData	Areas outside survey boundary are coded as NoData. Internal voids (e.g., open water areas) are coded as NoData (-999999)	Pass
Hydro-flattening	Ensure DEMs were hydro-flattened or hydro-enforced as required by project specifications	Pass
Monotonicity	Verify monotonicity of all linear hydrographic features	Pass

Parameter	Requirement	Pass/Fail
Breakline Elevations	Ensure adherence of breaklines to bare-earth surface elevations, i.e., no floating or digging hydrographic feature	Pass
Bridge Removal	Verify removal of bridges from bare-earth DEMs and no saddles present	Pass
DEM Artifacts	Correct any issues in the lidar classification that were visually expressed in the DEMs. Reprocess the DEMs following lidar corrections.	Pass
DEM Tiles	Split the DEMs into tiles according to the project tiling scheme	Pass
DEM Formatting	Verify all properties of the tiled DEMs, including coordinate reference system information, cell size, cell extents, and that compression is not applied to the tiled DEMs. GDAL version 2.4.0 used for all DEM formatting.	Pass
DEM Extents	Load all tiled DEMs into Global Mapper and verify complete coverage within the (buffered) project boundary and verify that no tiles are corrupt	Pass

5.3 DEM Vertical Accuracy Results

The same 158 checkpoints that were used to test the vertical accuracy of the lidar were used to validate the vertical accuracy of the final DEM products. Accuracy results may vary between the source lidar and final DEM deliverable. DEMs are created by averaging several lidar points within each pixel, which may result in slightly different elevation values at each survey checkpoint when compared to the linearly interpolated TIN created from the source LAS. The vertical accuracy of the DEM was tested by comparing the elevation of a given surveyed checkpoint with the elevation of the horizontally coincident pixel in the DEM. Dewberry used Esri software to test the DEM vertical accuracy.

Out of the 163 checkpoints received from the surveyor, four were determined to be unusable in the final DEM accuracy testing due to their location on unsuitable surfaces. These checkpoints were omitted from the DEM accuracy testing. The coordinates for the removed checkpoints are provided in the table below.

Table 20. Checkpoints omitted from DEM vertical accuracy testing

Point ID	UTM Zone 15N NAD83(2011), m		NAVD88 Geoid 18, m		Delta Z (m)
	Easting (X)	Northing (Y)	Survey Z	Lidar Z	
NVA_138	784564.830	3276167.065	0.966	-0.6	1.566
NVA_139	795208.334	3276848.101	0.335	0.454	0.119
NVAH_017	803515.822	3308673.683	0.624	0.621	-0.003
VVA_079	827099.933	3250879.552	0.458	-0.6	-1.058

The table below summarizes the tested vertical accuracy results from the final DEM dataset.

Table 21. DEM vertical accuracy results

Land Cover Category	# of Points	NVA (m)	VVA (m)
Project Specification	**155**	**0.196**	**0.300**
NVA	93	0.140	-
VVA	65	-	0.278

This DEM dataset was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 10.0 cm RMSEz vertical accuracy class. Actual NVA accuracy was found to be $RMSE_z$ = 7.2 cm, equating to ± 7.2 cm at 95% confidence level. Actual VVA accuracy was found to be ± 27.8 cm at the 95th percentile.

Table 22 lists the 5% outliers that are larger than the VVA 95th percentile.

Table 22. DEM VVA 5% outliers

Point ID	UTM Zone 15N NAD83(2011), m		NAVD88 Geoid 12B, m		Delta Z, m
	Easting (X)	Northing (Y)	Survey Z	Lidar Z	
VVA_046	800193.596	3275717.092	0.205	0.483	0.278
VVA_067	854813.387	3238909.738	0.635	1.140	0.505
VVA_072	844625.421	3295616.480	0.184	0.488	0.304
VVA_022	809050.379	3309608.826	-0.740	-0.365	0.375

Table 23 provides overall descriptive statistics.

Table 23. DEM vertical accuracy descriptive statistics

Land Cover Type	# of Points	$RMSE_z$ (m)	Mean (m)	Median (m)	Skew	Std Dev (m)	Min (m)	Max (m)	Kurtosis
NVA	93	0.072	0.027	0.027	-0.504	0.071	-0.148	0.129	-0.364
VVA	65	-	0.025	0.032	-0.515	0.073	-0.194	0.186	0.480

Based on the vertical accuracy testing conducted by Dewberry, the DEM dataset for the USGS Louisiana Coastal Lidar Project satisfies the project's pre-defined vertical accuracy criteria.

7. DERIVATIVE LIDAR PRODUCTS

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

6.1 Swath Separation Images (SSIs)

Dewberry verified inter-swath or between swath relative accuracy of the dataset by generating swath separation images in conjunction with interswath polygons. Color-coding is used to help visualize elevation differences between overlapping swaths. Pixels that do not contain points from overlapping flight lines are colored according to their intensity values.

The swath separation images are symbolized by the following ranges:

- 0-8 cm: **Green**
- 8-16 cm: **Yellow**
- >16 cm: **Red**

Areas of vegetation and steep slopes (slopes with 16 cm or more of valid elevation change across one raster pixel) are expected to appear yellow or red in the SSIs. Flat, open areas are expected to be green in the SSIs. Large or continuous sections of yellow or red pixels following flight line patterns and not the terrain or vegetation can indicate the data was not calibrated correctly or that there were issues during acquisition that could affect the usability of the data.

Dewberry generated swath separation images using LP360 software. These images were created from the last return of all points except points classified as noise and/or flagged as withheld. Point Insertion was used as the Surface Method and the cell size was set to the deliverable DEM cell size. The three interval bins used are bulleted above and the parameter to “Modulate source differences by Intensity” was set to 50%. The output GeoTIFF rasters are tiled to the project tile grid, clipped to the master DPA, and formatted (including defining the CRS which matches the project CRS) using GDAL software, version 2.4.0.

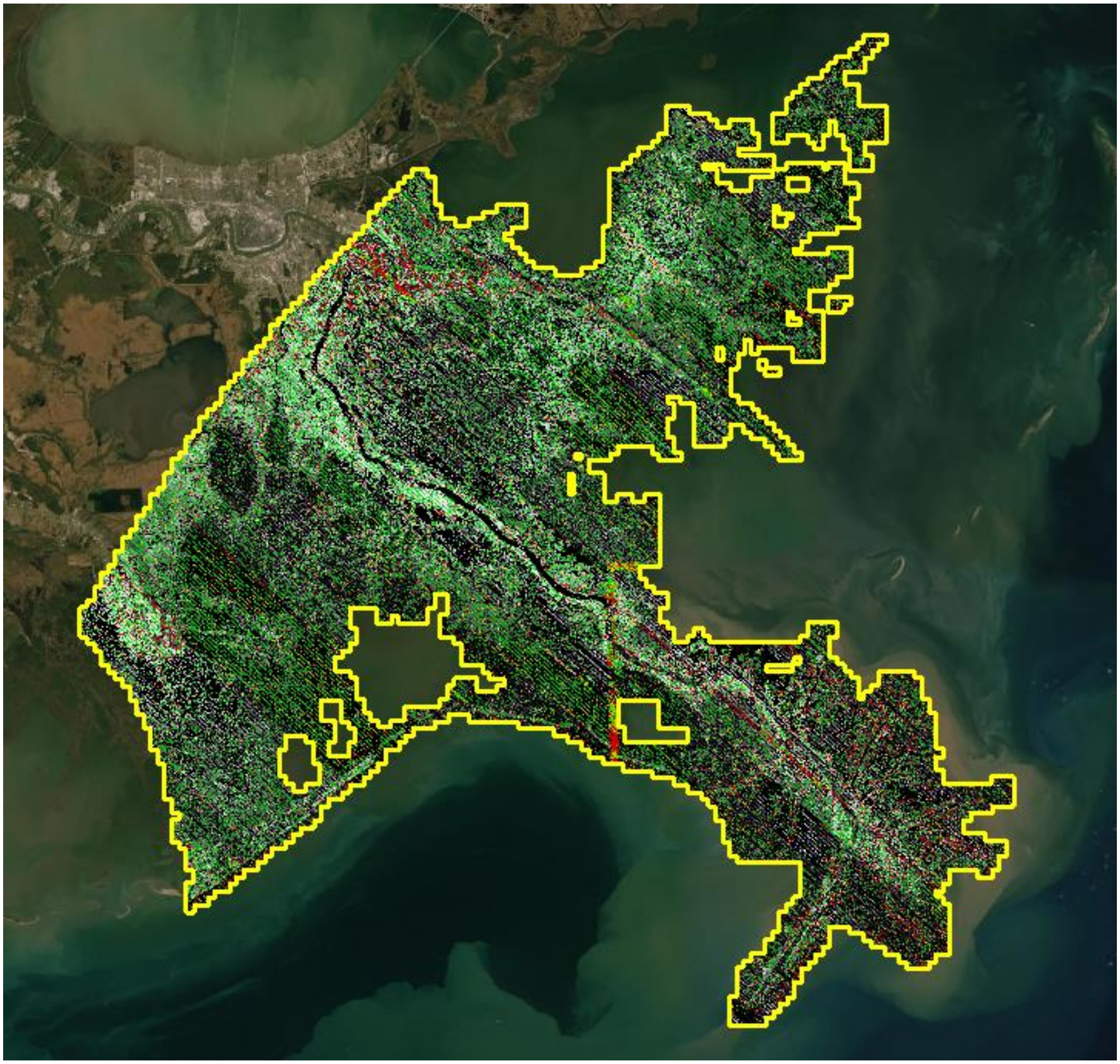


Figure 10. Swath Separation Images (SSIs) generated for the Louisiana Coastal Project.

6.2 Interswath and Intraswath Polygons

6.2.1 Interswath Accuracy

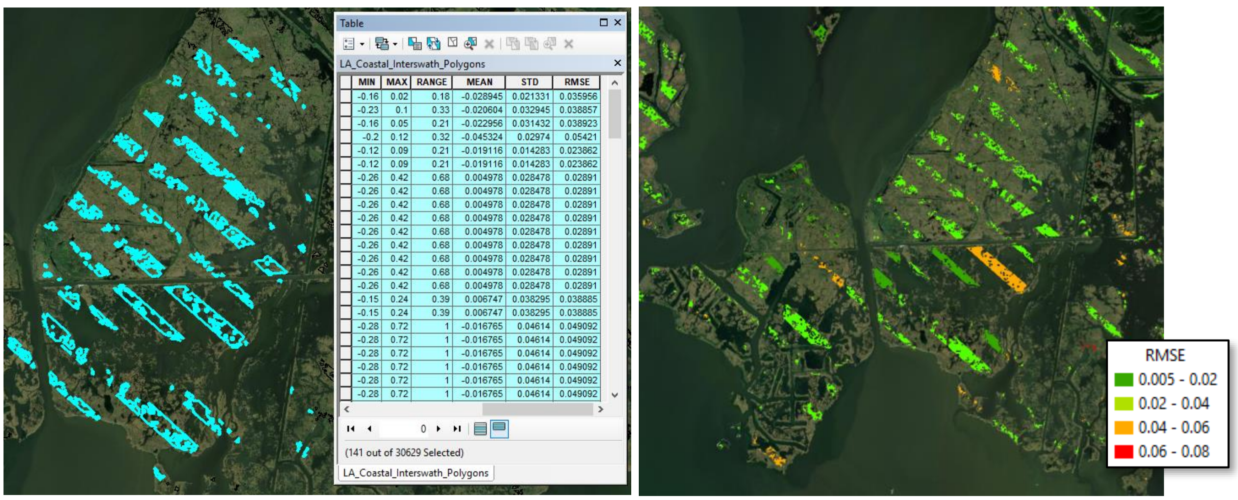
The Interswath accuracy, or overlap consistency, measures the variation in the lidar data within the swath overlap. Interswath accuracy measures the quality of the calibration or boresight adjustment of the data in each lift. Per USGS specifications, overlap consistency was assessed at multiple locations within overlap in non-vegetated areas of only single returns and on slopes less than 10 degrees. As with precision, the interswath consistency was reported by way of a polygon shapefile delineating the sample areas checked and attributed with the following and using the cells within each polygon as sample values:

- Minimum difference in the sample area (numeric)

- Maximum difference in the sample area (numeric)
- RMSDz (Root Mean Square Difference in the vertical/z direction) of the sample area (numeric). Intraswath Accuracy

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

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



MIN	MAX	RANGE	MEAN	STD	RMSE
-0.16	0.02	0.18	-0.028945	0.021331	0.035956
-0.23	0.1	0.33	-0.020604	0.032945	0.038857
-0.16	0.05	0.21	-0.022956	0.031432	0.038923
-0.2	0.12	0.32	-0.045324	0.02974	0.05421
-0.12	0.09	0.21	-0.019116	0.014283	0.023862
-0.12	0.09	0.21	-0.019116	0.014283	0.023862
-0.26	0.42	0.68	0.004978	0.028478	0.02891
-0.26	0.42	0.68	0.004978	0.028478	0.02891
-0.26	0.42	0.68	0.004978	0.028478	0.02891
-0.26	0.42	0.68	0.004978	0.028478	0.02891
-0.26	0.42	0.68	0.004978	0.028478	0.02891
-0.26	0.42	0.68	0.004978	0.028478	0.02891
-0.26	0.42	0.68	0.004978	0.028478	0.02891
-0.26	0.42	0.68	0.004978	0.028478	0.02891
-0.26	0.42	0.68	0.004978	0.028478	0.02891
-0.15	0.24	0.39	0.006747	0.038295	0.038885
-0.15	0.24	0.39	0.006747	0.038295	0.038885
-0.28	0.72	1	-0.016765	0.04614	0.049092
-0.28	0.72	1	-0.016765	0.04614	0.049092
-0.28	0.72	1	-0.016765	0.04614	0.049092
-0.28	0.72	1	-0.016765	0.04614	0.049092
-0.28	0.72	1	-0.016765	0.04614	0.049092
-0.28	0.72	1	-0.016765	0.04614	0.049092

Figure 11. Left: Example interswath polygons and example statistics. Right: Example interswath polygons colored by RMSDz values.

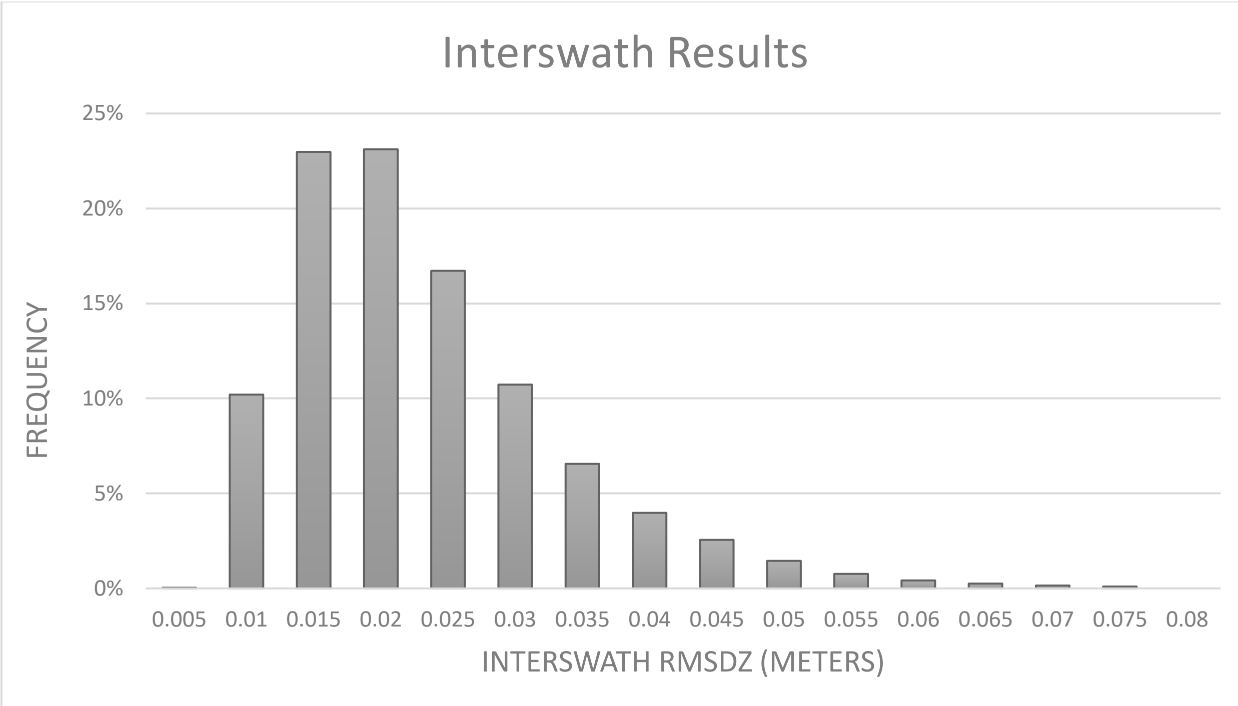


Figure 12. Frequency distribution of interswath RMSDz results for the Louisiana Coastal project.

6.2.2 Intraswath Accuracy

The intraswath accuracy, or the precision of lidar, measures variations on a surface expected to be flat and without variation. Precision is evaluated to confirm that the lidar system is performing properly and without gross internal error that may not be otherwise apparent. To measure the precision of a lidar dataset, level or flat surfaces were assessed. Swath data in non-overlap areas were assessed using only first returns in non-vegetated areas.

Precision was reported by way of a polygon shapefile delineating the sample areas checked and attributed with the following and using the cells within each polygon as sample values:

- Minimum slope-corrected range (numeric)
- Maximum slope-corrected range (numeric)
- RMSDz of the slope-corrected range (numeric).

Dewberry manually created intraswath polygons where hard surfaces exist within the project area. The intraswath polygon distribution is illustrated in Figure 13. The statistics outlined above were then generated per polygon and each polygon was reviewed for acceptability, issues, and trends.

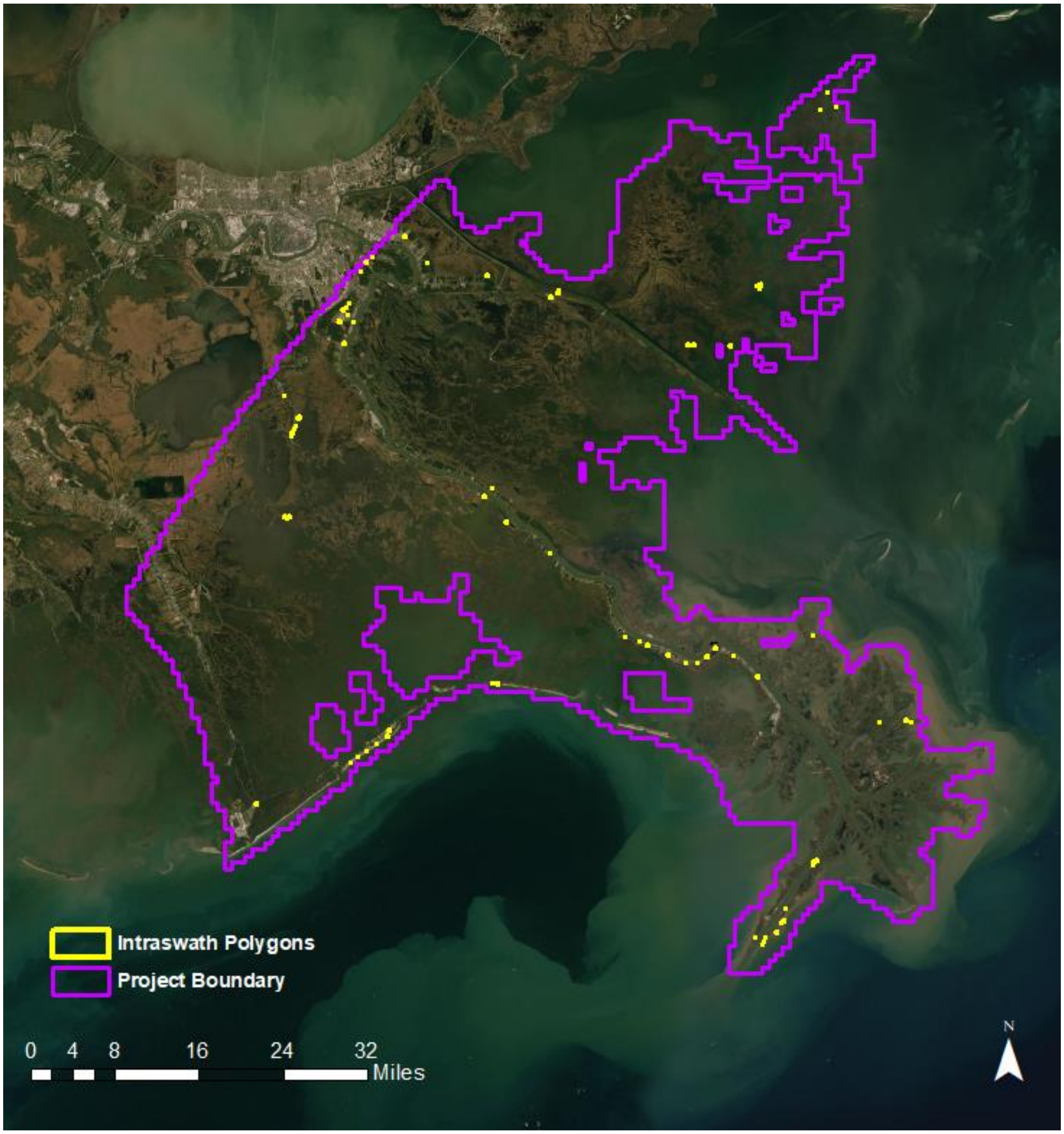


Figure 13. Intraswath polygons used to test intraswath vertical accuracy.

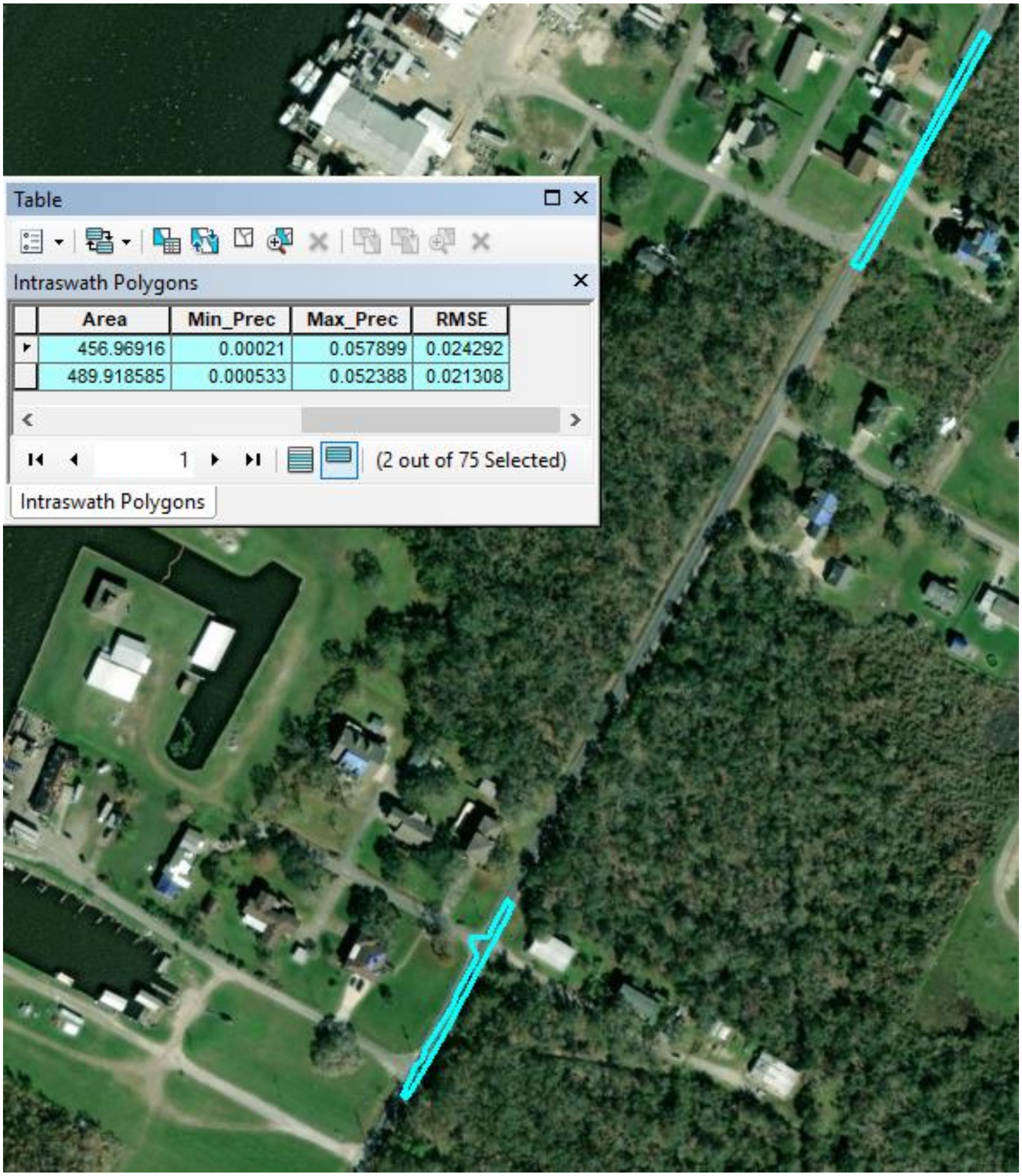


Figure 14. Example test polygon for intraswath testing, and its results.

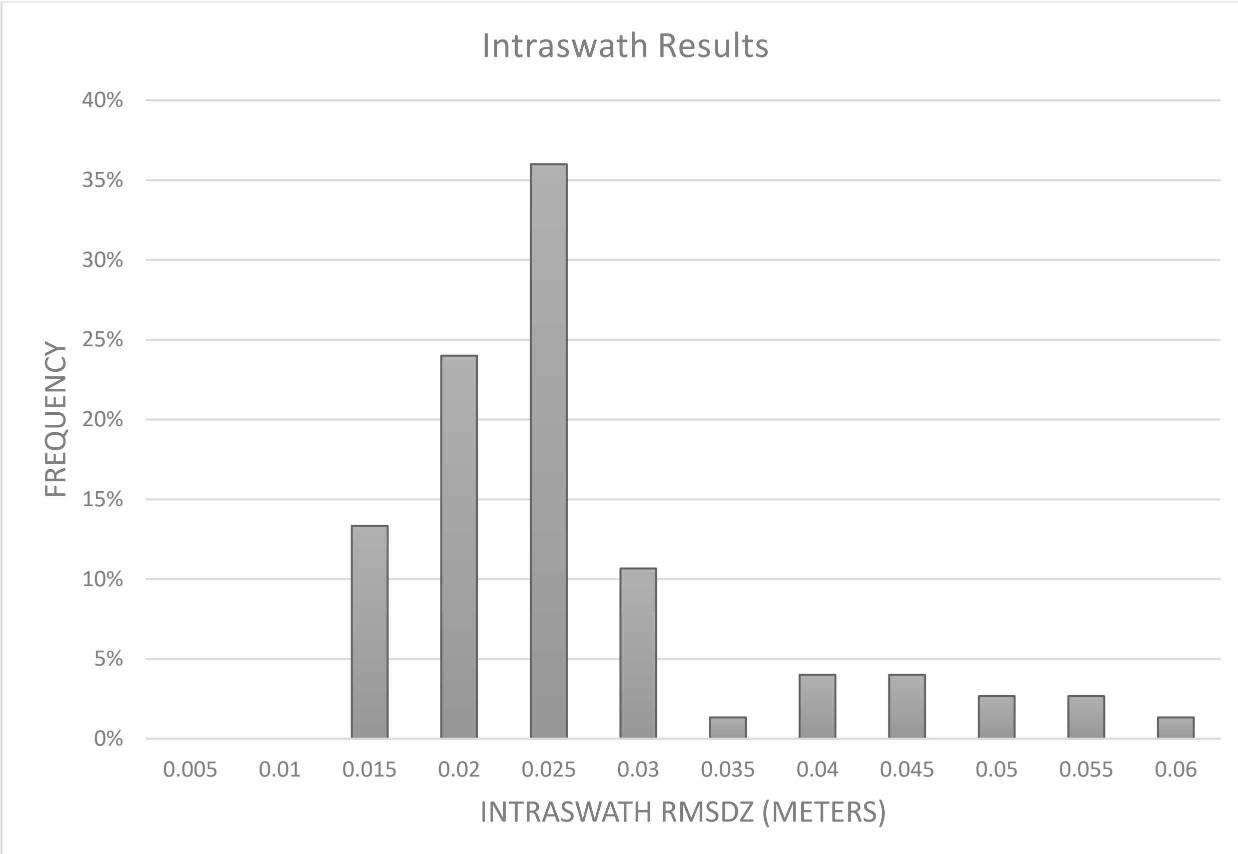


Figure 15. Frequency distribution of intraswath RMSDz results for the Louisiana Coastal project.

6.3 Maximum Surface Height Rasters (MSHRs)

MSHRs are delivered as tiled GeoTIFFs (32-bit, floating point), with the tile size and naming convention matching the project tile grid, tiled point cloud, and tiled DEM deliverables. MSHRs are provided as proof of performance that Dewberry's withheld bit flag has been properly set on all points, including noise, which are not deemed valid returns and which should be excluded from all derivative product development. All points, all returns, excluding points flagged as withheld, are used to produce MSHRs. The rasters are produced with a binning method in which the highest elevation of all lidar points intersecting each pixel is applied as the pixel elevation in the resulting raster. Final MSHRs are formatted using GDAL software version 2.4.0, spatially defined to match the project CRS, and the cell size equals the deliverable DEM cell size (unless lidar density at the defined DEM cell size is insufficient for MSHR analysis and then a larger cell size for the MSHRs may be used). Prior to delivery, all MSHRs are reviewed for complete coverage, correct formatting, and any remaining point cloud misclassifications specifically in regard to the use of the withheld bit.

6.4 Flightline Extents GDB

Flightline extents are delivered as polygons in an Esri GDB, delineating actual coverage of each swath used in the project deliverables. Dewberry delivered this GDB using USGS's provided template so that each polygon contains the following attributes:

- Lift/Mission ID (unique per lift/mission)
- Point Source ID (unique per swath)
- Type of Swath (project, cross-tie, fill-in, calibration, or other)
- Start time in adjusted GPS seconds
- End time in adjusted GPS seconds

Prior to delivery, a final flightline GDB is created from the final, tiled point cloud deliverables to ensure all correct swaths are represented in the flightline GDB. The flightline GDB is then reviewed for complete coverage and correct formatting.