Lidar Mapping Report

TX_LowerRioGrande_D22 - 140G0222F0295 MOD P00001

Project ID 300034 | Work Unit ID 300257

Contract: 140G0221D0010 | November 30, 2023
Version 02
U. S. GEOLOGICAL SURVEY

Document Control

Document Information

Project Title	USGS_TX_LowerRioGrande_D22
Document Title	Lidar Mapping Report
Fugro Project No.	04.00218030
Issue Status	Version 02

Client Information

Client	U. S. GEOLOGICAL SURVEY

Revision History

Issue	Date	Status	Comments on Content	Prepared By	Reviewed By
01	07/27/23	For Review	Awaiting client comments	SP	
02	11/30/23	For Review	Awaiting client comments	SP	

1. Data Acquisition and Processing

The TX_LowerRioGrande_D22 task is for a high-resolution data set of QL1+ (30ppsm) and QL1 (8ppsm) lidar of approximately 3,122 square miles in the state of Texas. These counties include parts of Starr, Hidalgo, Willacy, and Cameron. The TX_LowerRioGrande_D22 project will support the United States Geological Survey (USGS) and their partners by providing high-quality topographic data critical to making decisions, ranging from immediate safety of life, property, and environment to long term planning for infrastructure projects. This Lidar Mapping Report pertains to the Block 1 30 ppsm AOI, Work Unit ID 300257.

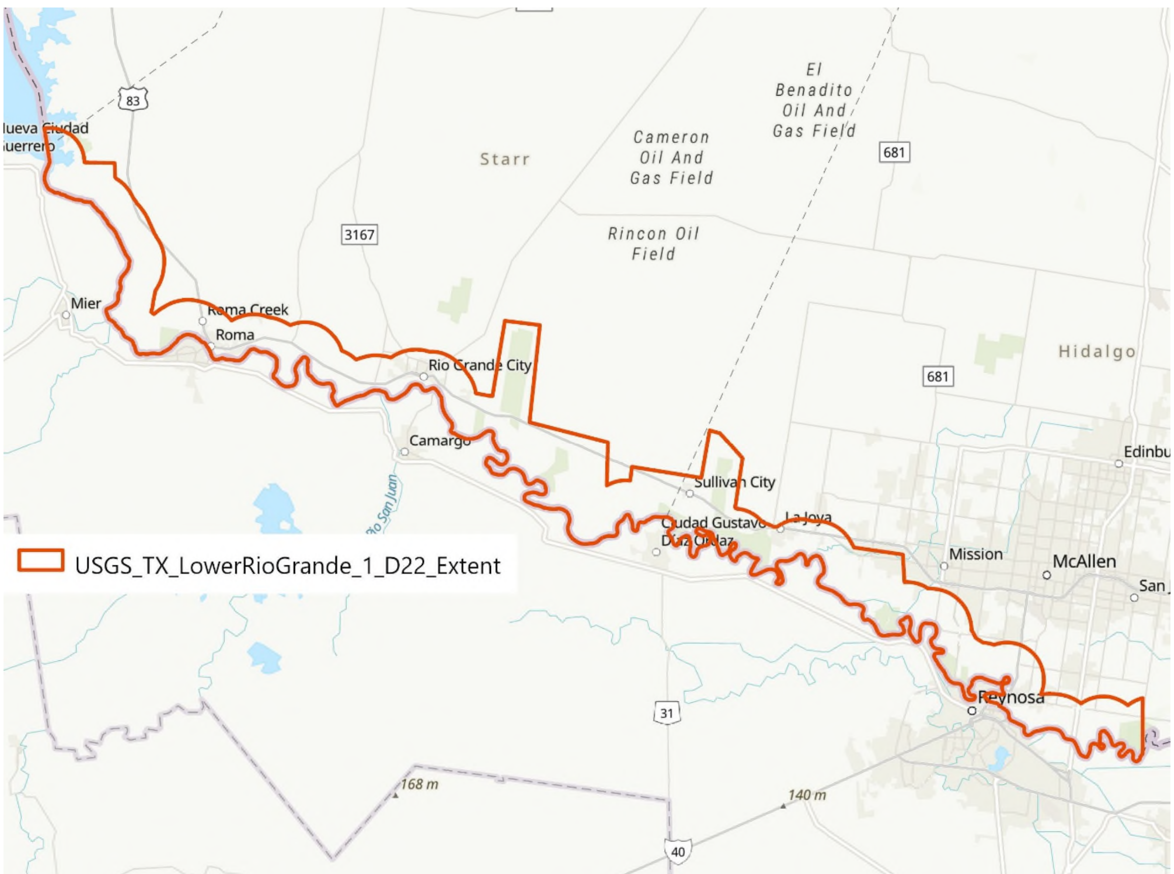


Figure 1: Work Unit Extent

1.1 Sensor

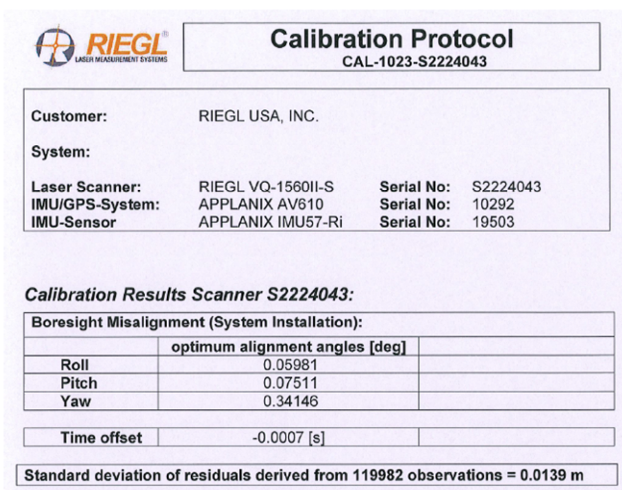
1.1.1 Settings

Block 1 was collected using The Riegl VQ-1560 II-S sensor using the following parameters/settings:

- Aggregate Nominal Pulse Spacing (ANPS): 0.18 Meters; 30ppsm (QL1+)
- Scan Angle: 58.52 degrees
- Pulse Rate: 4,000,000 hz
- Scan Rate: 534
- Swath Width: 3810' (1161 meters)
- Sidelap: 20%
- Flight Height: 3400' AMT
- Flight Speed: 149 knots

1.1.2 Calibration

The Roll-Pitch-Yaw correction (standard boresight) for each swath is applied on a collection or block basis (see Section 2.1.1 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

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 LRG_GNSS_IMU_plots.zip 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 0.18 m 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.
- Thorough review of the data was performed to identify any data gaps in project area.
- 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 0.18 m 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.

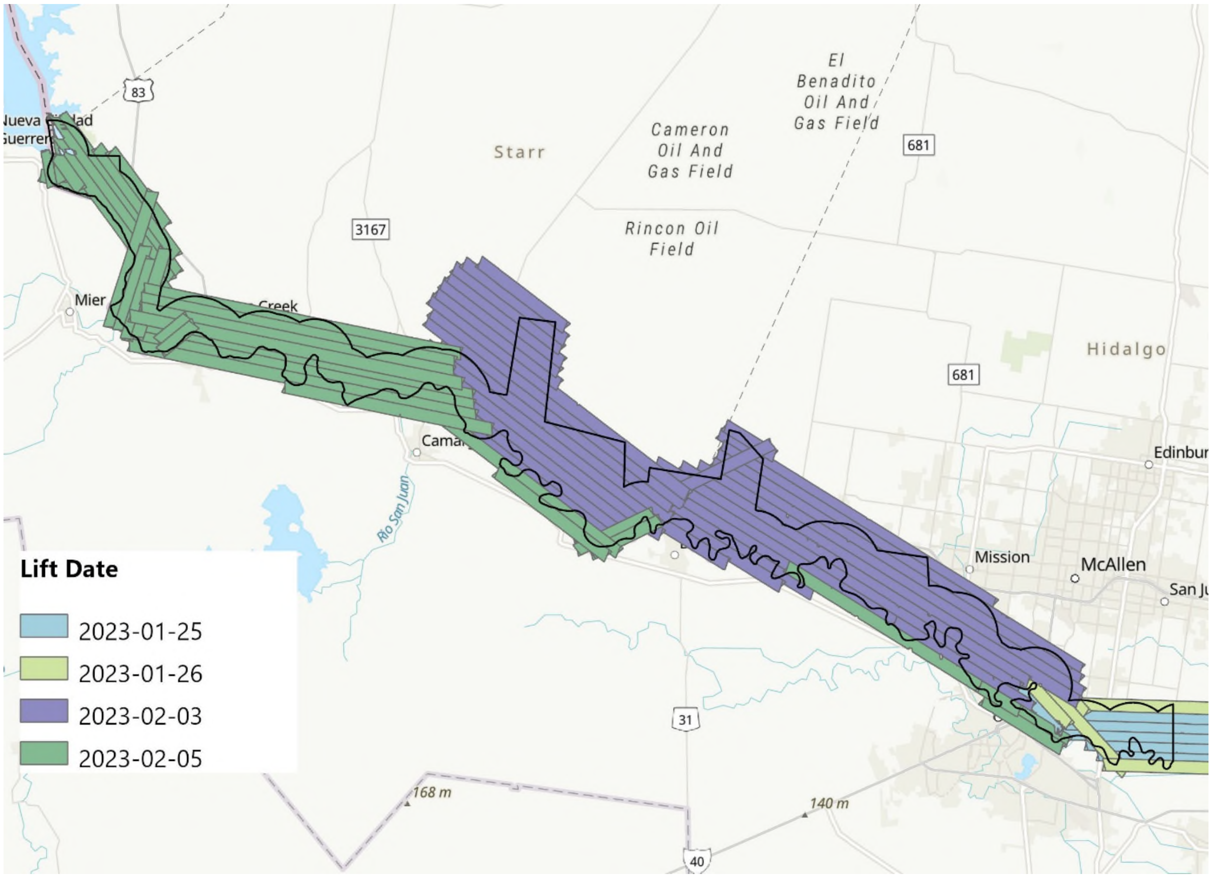


Figure 3: Flightline vectors

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.

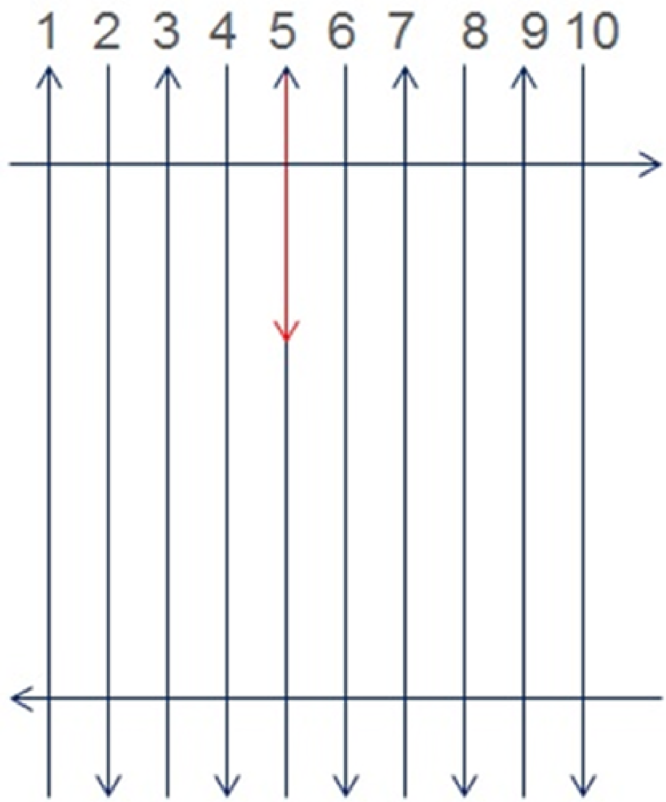


Figure 4: Example production block: North-south are production lines, east-west are cross ties, calibration flight line shown in red.

- 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 $RMSE_Z$ (non-vegetated) ≤ 10 cm, NVA ≤ 19.6 cm 95% Confidence Level (Required Accuracy) was met (04/06/23).

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 using Geocue version 2020.1.22.2 (64bit) 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 CloudPro 1.2.4 (Build 106713) and RiProcess 1.4.2, 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 re-classified 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: UTM Zone 14 north, NAD83 (2011), meters, NAVD88 (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. Buildings and vegetation were automatically classified on the cloud using Sense.Lidar™ and did not receive any rigorous manual editing. The classification was then reviewed and finalized using Terrascan. 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:

(01) Class 1 – Processed, but unclassified
(02) Class 2 – Bare earth ground
(03) Class 3 – Low Vegetation (0 – 1 meter; automated classification)
(04) Class 4 – Medium Vegetation (1-3 meters; automated classification)
(05) Class 5 – High Vegetation (>3 meters; automated classification)
(06) Class 6 - Buildings
(07) Class 7 – Low Noise
(09) Class 9 – Water
(17) Class 17 – Bridge Decks
(18) Class 18 – High Noise
(20) Class 20 – Ignored Ground (Breakline Proximity)

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

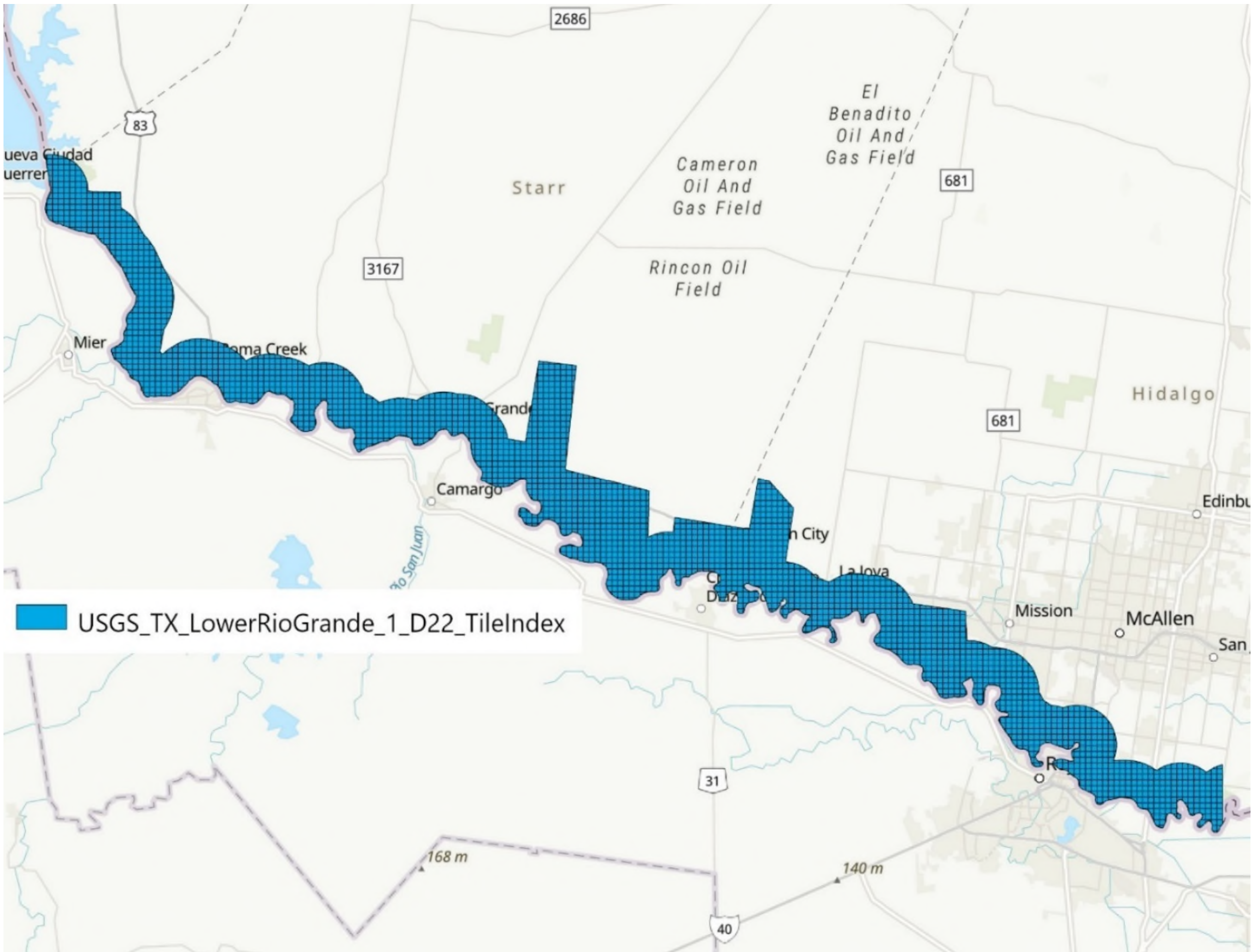


Figure 5: Delivery Block Tiles

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 0.25 meter. 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 geodatabase.

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 0.25-meter 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.

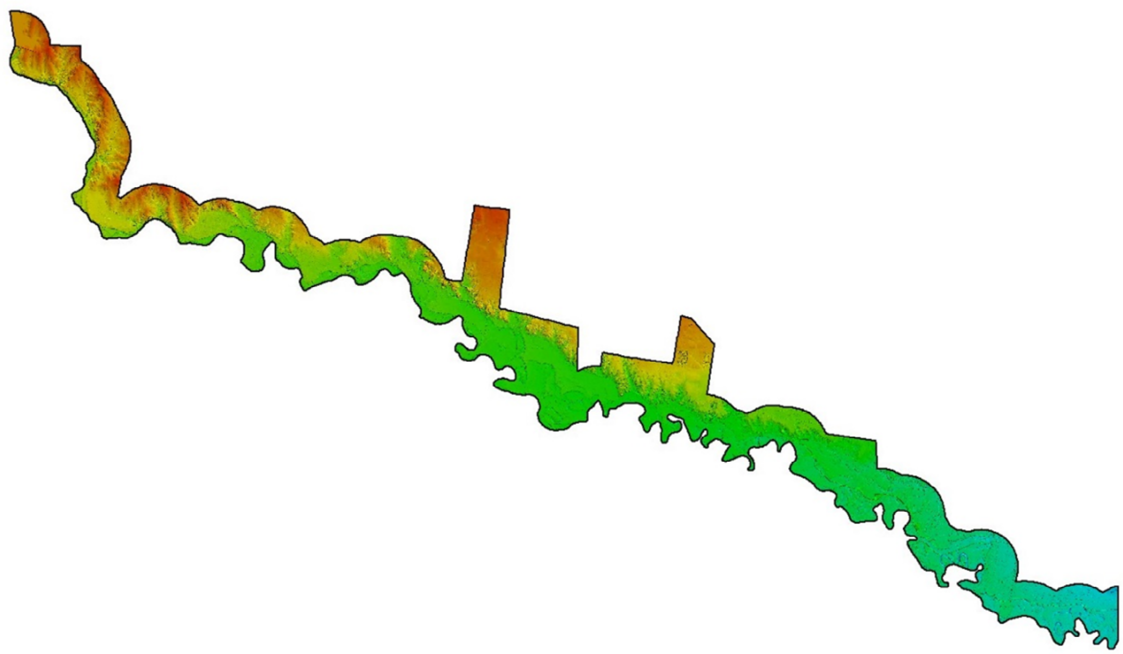


Figure 6: Delivery Block Shaded Relief

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.

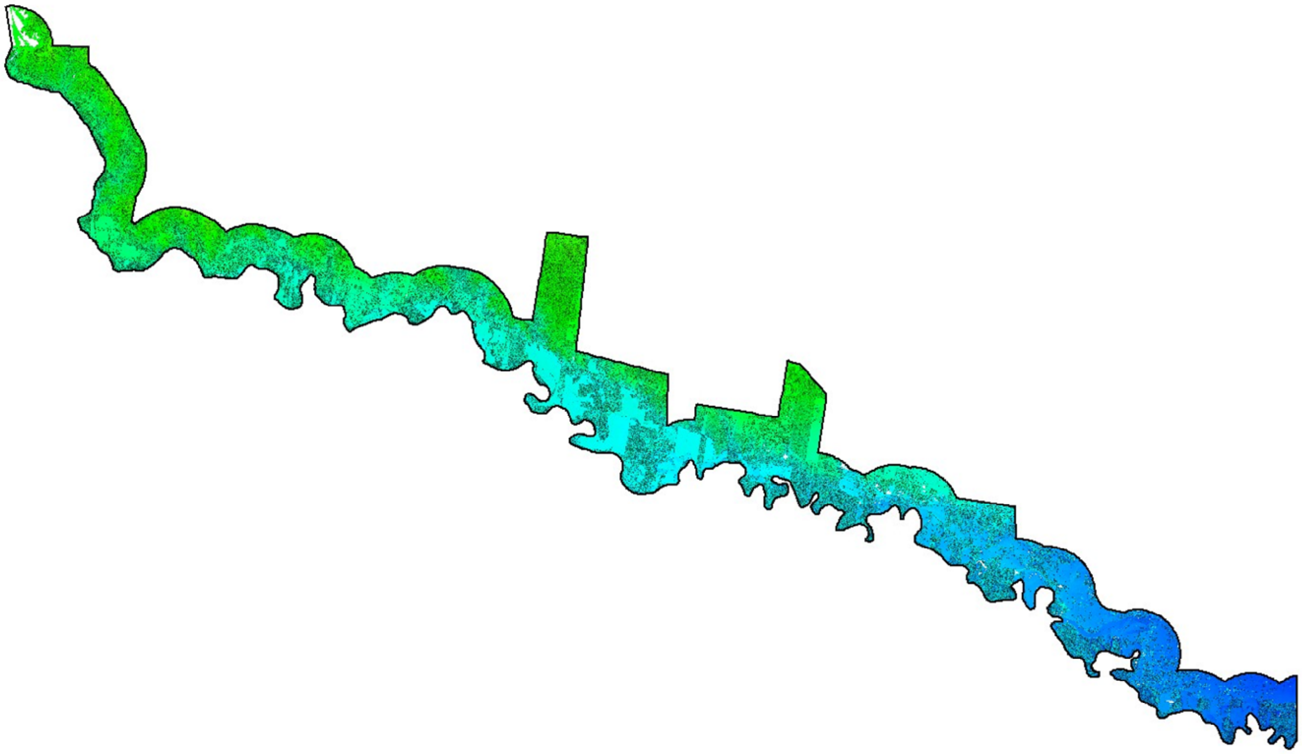


Figure 7: Maximum Surface Height Rasters

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 as polygons in Esri Geodatabase.

2.4.5 Intensity Images

Intensity images were generated from the lidar first returns.

The pixel size is 0.25 meter. The rasters were tiled to match all other tiled products and delivered in 8-bit, 256 color grayscale, GeoTIFF format.

2.4.6 Vegetation Rasters

Canopy height rasters were generated from the classified lidar. Pixel values represent the top of the vegetation surface minus the ground surface.

Canopy density rasters were also generated from the classified lidar. Pixel values represent the point-averaged vegetation density (the vegetation point-count divided by the point-count that fall within the pixel).

The pixel size is 0.5 meter. The rasters were tiled to match all other tiled products and delivered in 32-bit floating point GeoTIFF format.

2.4.7 Building Footprints

2D Building footprint polygon features for buildings > 20 square meters were extracted using the Class 6 lidar building points classified through the automated Sense.Lidar™ process. The technicians used Terrascan, ArcGIS and Fugro proprietary software to produce lidar-derived automatic building footprints. Building footprints were delivered as polygon features in Esri shape file format.

2.4.8 Building Models

3D buildings were automatically generated for buildings > 20 square meters. The technicians generated difference sets of surface models to extract surface information. DTMs and DSMs were generated from the LAS dataset by filtering required point classifications and converting to a raster dataset. A nDSM was generated to extract feature height information by subtracting the DTM from the DSM. Basic roof forms were then extracted. This activity included creation of simple flat roof block buildings from the automated 2D building footprints and the elevation surface to include building base elevation and building height. 3D buildings features were delivered as multipatch features in Esri shape file format.

3. Important Note on Tile Coverage

Classified Point Cloud, Vegetation Rasters, MSHRs and Swath Separation Images:

There were 11 tiles in the final tile layout that do not contain any lidar points. 10 of those tiles are empty due to the clipped version only containing water with no returns. This occurred in 8 tiles along the Rio Grande River, and 2 tiles in the northwest corner near the Falcon Power Plant dam. There was 1 tile (14RNQ380020_a), that did not contain any lidar points because the clipped version was extremely small, only 0.6 meters. The missing lidar have been replaced with empty .txt text files using the tile naming convention so that file count and naming is consistent throughout deliverable folders. Below is a list of the 11 tile names that are missing Classified Point Cloud, Vegetation Rasters, MSHRs and Swath Separation Image coverage:

```
14RMQ820400_b - zero points in tile because clipped tile only contains water with no returns.
14RMQ820400_c - zero points in tile because clipped tile only contains water with no returns.
14RNP550990_c - zero points in tile because clipped tile only contains water with no returns.
14RNQ410030_d - zero points in tile because clipped tile only contains water with no returns.
14RNQ370030_b - zero points in tile because clipped tile only contains water with no returns.
14RNQ200130_a - zero points in tile because clipped tile only contains water with no returns.
14RNQ070170_c - zero points in tile because clipped tile only contains water with no returns.
14RMQ860330_a - zero points in tile because clipped tile only contains water with no returns.
14RMQ890220_d - zero points in tile because clipped tile only contains water with no returns.
14RMQ890210_b - zero points in tile because clipped tile only contains water with no returns.
14RNQ380020_a - zero points in tile because clipped tile is extrememly small, only 0.6 meters.
```

Intensity Images and Bare Earth Raster DEM:

For the same reason as mentioned above, 3 tiles have been replaced with empty .txt text files using the tile naming convention so that file count and naming is consistent throughout deliverable folders. Below is a list of the 3 tile names that are missing Intensity Images and Bare Earth Raster DEM coverage:

4rmq820400_b_.txt

14rmq820400_c.txt

14rnq380020_a.txt

4. Accuracy reporting

Data collected under this Task Order meets the National Standard for Spatial Database Accuracy (NSSDA) accuracy standards. The NSSDA standards specify that vertical accuracy be reported at the 95 percent confidence level for data tested by an independent source of higher accuracy.

4.1 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.

4.2 Horizontal Accuracy

This data set was produced to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 20.2 (cm) RMSEx / RMSEy Horizontal Accuracy Class which equates to Positional Horizontal Accuracy = +/- 49.4 cm at a 95% confidence level.

4.3 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 (ACCZ) is: 19.6 cm at a 95% confidence level, derived according to NSSDA, i.e., based on RMSEZ of 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.

Table 1: Accuracy of the Lidar Point Cloud Data

Raw Flight Lines	RMSEz (non-vegetated)	NVA at 95-percent confidence level
Specification (cm)	≤ 10	≤ 19.6
Calculated Values (cm)	2.9	5.6
Specification (m)	≤ 0.100	≤ 0.196
Calculated Values (m)	0.029	0.056
Number of points	86	86

Bare Earth Surface: The accuracy (ACCZ) of the derived DEM was calculated and is being reported in three (3) ways:

1. **RMSEZ (Non-Vegetated):** The required RMSEZ is ≤ 10 cm.
2. **Non-Vegetated Vertical Accuracy (NVA):** The required NVA is: ≤ 19.6 cm at a 95% confidence level, derived according to NSSDA, i.e., based on RMSEZ of 10 cm in the "open terrain" and/or "Urban" land cover categories. This is a required accuracy.
3. **Vegetated Vertical Accuracy (VVA):** The required VVA is: ≤ 29.4 cm at a 95th percentile level, derived according to ASPRS Guidelines, Vertical Accuracy for Reporting LiDAR Data, i.e., based on the 95th percentile error in Vegetated land cover categories combined (Tall Grass, Brush, Forested Areas). This is a required accuracy.

Please refer to table 2 and 3 below for the achieved accuracies within Work Unit 300257.

Table 2: Accuracy of the classified point cloud (WU 300257)

LAS UTM14	RMSEz (non-vegetated)	NVA at 95-percent confidence level	VVA at 95th percentiles
Specification (cm)	≤ 10	≤ 19.6	≤ 29.4
Calculated Values (cm)	4.6	8.6	16.0
Specification (m)	≤ 0.100	≤ 0.196	≤ 0.294
Calculated Values (m)	0.046	0.086	0.160
Number of points	13	13	11

Table 3: Accuracy of the Derived DEM (WU 300257)

DEM UTM14	RMSEz (non-vegetated)	NVA at 95-percent confidence level	VVA at 95th percentiles
Specification (cm)	≤ 10	≤ 19.6	≤ 29.4
Calculated Values (cm)	4.4	8.7	17.0
Specification (m)	≤ 0.100	≤ 0.196	≤ 0.294
Calculated Values (m)	0.044	0.087	0.170
Number of points	13	13	11

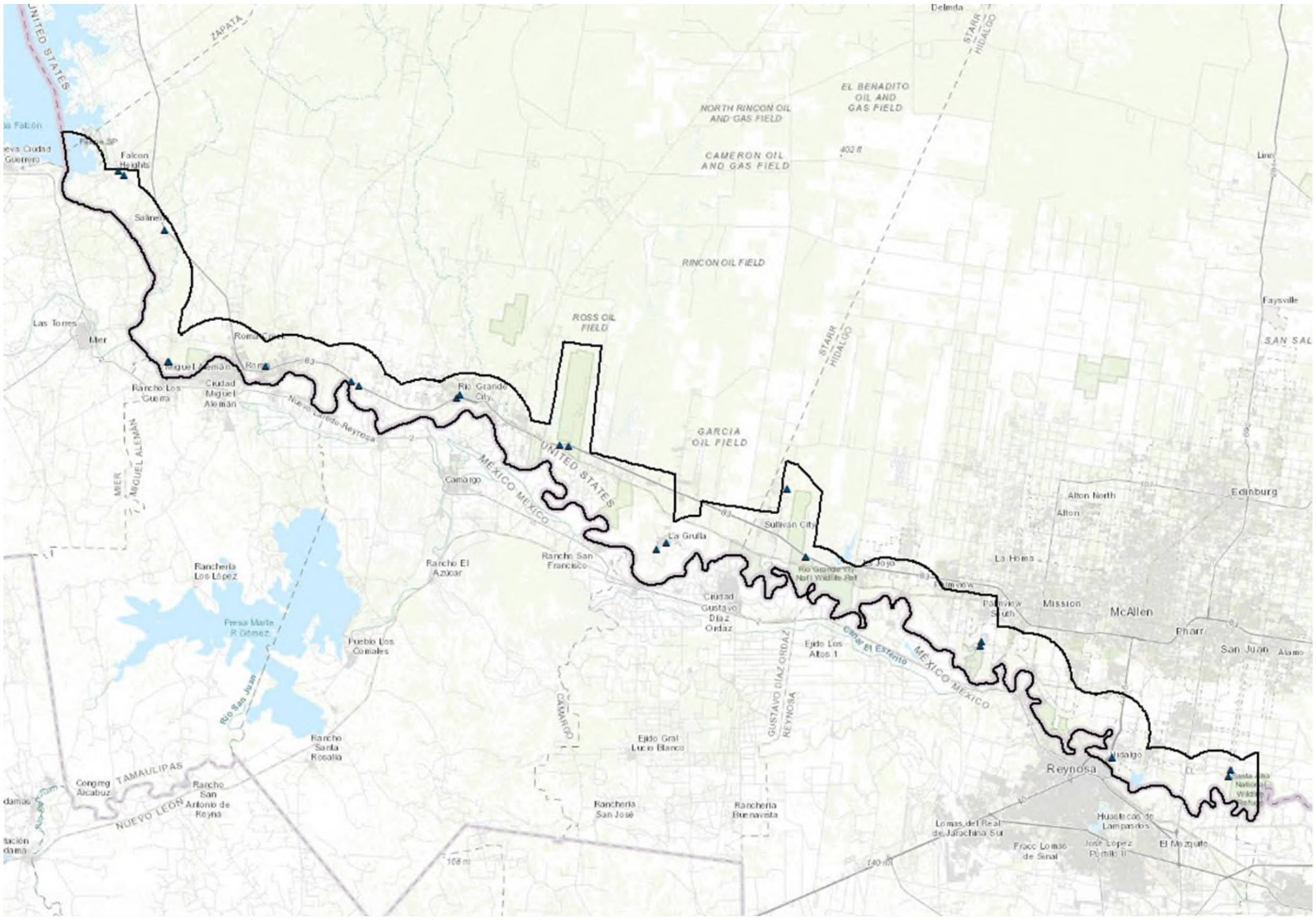


Figure 8: NVA and VVA Checkpoints - Classified Point Cloud & DEM

4.4 Relative Accuracy

4.4.1 Interswath Accuracy Analysis

Swath Separation Rasters are created at 1m resolution using 8cm threshold to show how the individual flightlines agree to one another in areas of overlap. The SSI imagery was generated using all points except high and low noise. This was performed using a tool developed inhouse. The output file format was GeoTIFF. Pixel color was based on vertical difference of swaths using the following breaks:

- 0-8 cm: GREEN;
- 8-16 cm: YELLOW;

- 16 cm or > last additional color ramp bin value: RED (for example, addition of ORANGE pixels for the range of 16-24 cm would require red pixels to represent > 24 cm).

An overview can be seen below:

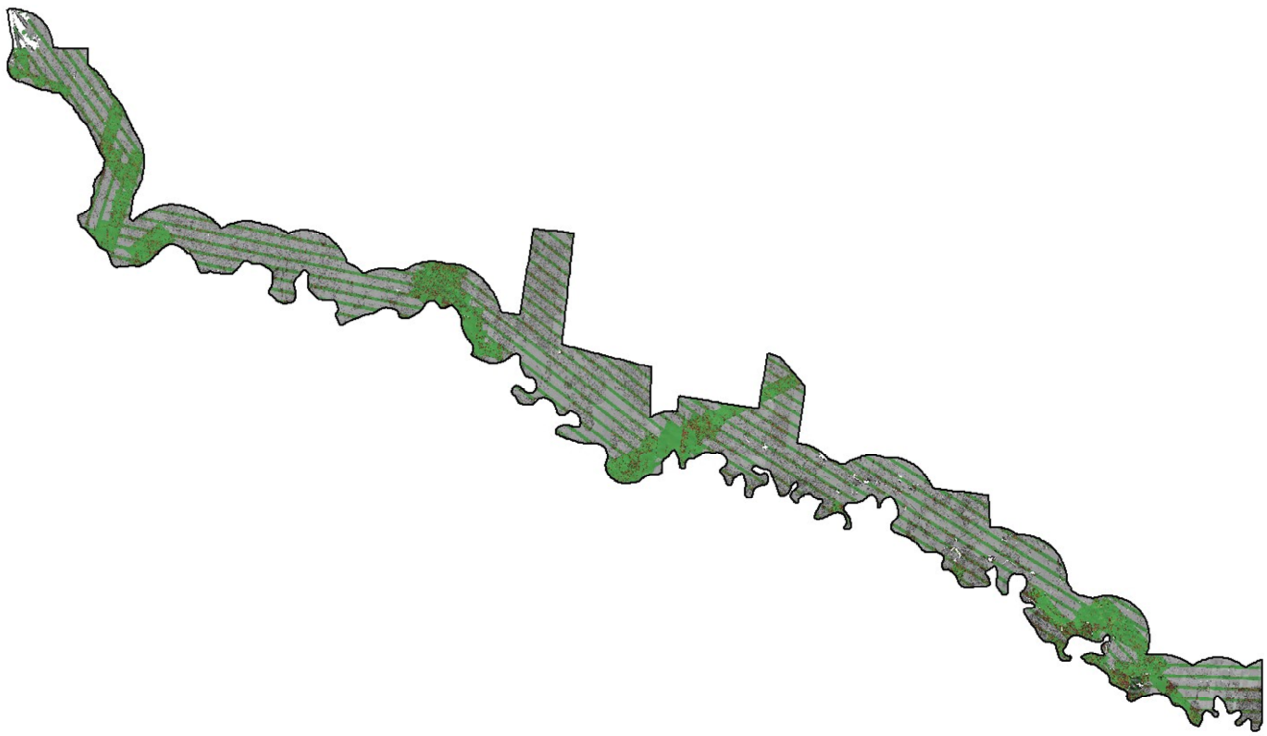


Figure 9: Swath Separation Images

Overlap Consistency: Overlap consistency is a measure of geometric alignment of two overlapping swaths; the principles used with swaths can be applied to overlapping lifts and projects as well. Overlap consistency is the fundamental measure of the quality of the calibration or boresight adjustment of the data from each lift and is of particular importance as the match between the swaths of a single lift is a strong indicator of the overall geometric quality of the data, establishing the quality and accuracy limits of all downstream data and products.

Overlap consistency was assessed at multiple locations within overlap in non-vegetated areas of only single returns.

Each overlap area was evaluated using a signed difference raster with a cell size equal to twice the ANPS, rounded up to the next integer. The difference rasters are visually examined using a bicolored ramp from the negative acceptable limit to the positive acceptable limit. Although isolated excursions beyond the limits are expected and accepted, differences in the overlaps shall not exceed the following limits:

1. Swath overlap difference, RMSDz ≤ 8 cm

2. Swath overlap difference, maximum ± 16 cm

The difference rasters are also statistically summarized to verify that root mean square difference in z (RMSDz) values do not exceed the project specifications. Consideration will be given for the effect of the expected isolated excursions over limits.

4.4.2 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 assessed using only single returns in non-vegetated areas. Repeatability was 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 assessed at multiple locations within hard surfaced areas (for example, parking lots or large rooftops).

Each sample area was 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.