Lidar Mapping Report

ND_3DEPProcessing_D22 | Block 4

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1. Data Acquisition and Processing

The ND_3DEPProcessing_D22 task is for processing of previously-collected high-resolution data set of QL2 (2ppsm) lidar of approximately 41,222 square miles of a base area of interest (AOI) over many counties in North Dakota. The source data was originally collected under the ND LiDAR Program Phases 7, 8 and 9. The ND_3DEPProcessing_D22 project will support dam safety assessments, engineering design and design reviews, conservation planning, research, delivery, floodplain mapping, and hydrologic modelling utilizing lidar technology. Sensors used for data collection on this project include the Leica Model ALS80 and Riegl model LMS-Q1560i.

Base Station

During lidar data collection the airborne GPS receiver was collecting data at 2 Hz frequency and the Dilution of Precision (PDOP) was monitored. GPS base stations were also running at the operational airports and were recording data at 1 Hz. The airborne GPS data was post-processed in DGPS mode together with base station data to provide high accuracy aircraft positions. The GPS trajectory then was combined with the IMU data using loosely coupled approach to yield high accuracy aircraft positions and attitude angles. Then the lidar data was processed using the aircraft trajectory and raw lidar data.

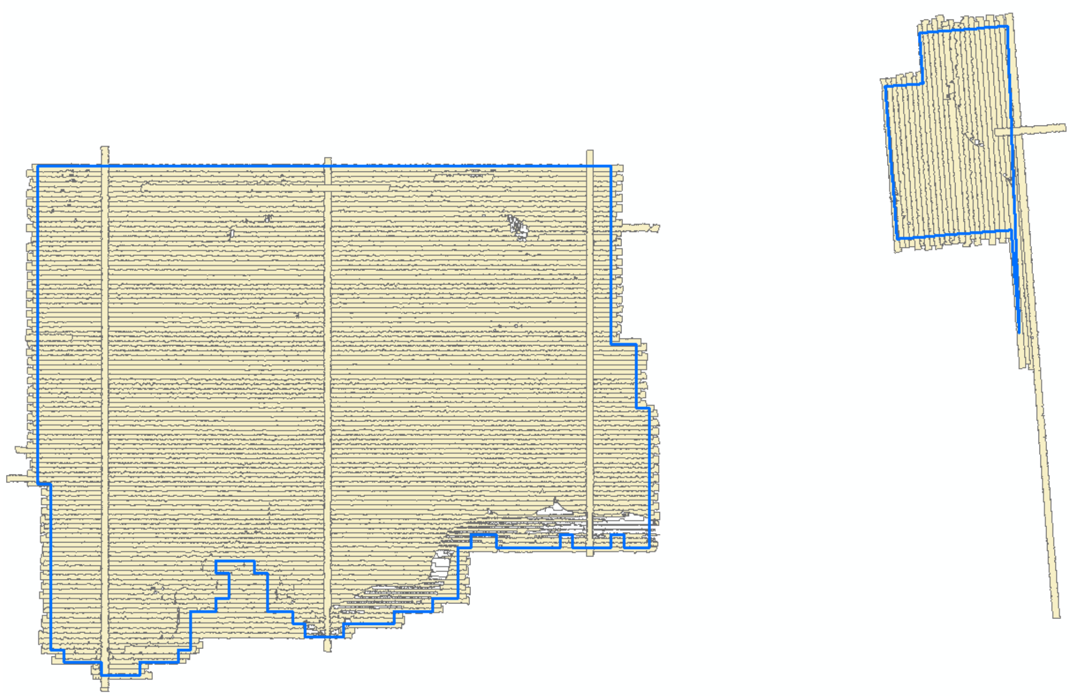

Figure 1: Flightline vectors

1.1 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.

1.1.1 GPS/IMU Processing

Airborne GPS and IMU data was processed using the airport GPS base station data. Waypoint Inertial Explorer (8.7) software is used to produce the final trajectory by combining the airborne GNSS-IMU and ground GNSS data to produce a Differential GNSS (DGNSS) solution. A DGNSS solution is calculated by determining the error of "fixed" ground GNSS base(s) and applying the error-correction to a "rover" GNSS dataset. All bases, "fixed" and "rover" datasets, must occupy a common duration to accomplish this.

The "fixed" XYZ ground GNSS base position(s) can be generated by using NOAA's OPUS (Online Positioning User Service) online utility. OPUS is a free service in the United States that uses the NOAA CORS network (NCN) to correct the XYZ coordinates of ground GNSS data.

1.1.2 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.

1.1.3 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.
- 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 0.71 m ANPS and also checked to make sure there is no clustering in point distribution.

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.

2.1.1 Raw Data Processing and Boresight

Raw data processing is the reduction of raw lidar, IMU, and GPS 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 GPS/IMU system to orient those ranges in 3D space and to produce XYZ points.

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 process:

- Technicians processed the raw data to LAS format flight lines using the final GPS/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. 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.
- Once the boresight angle calculation was completed for the selected areas, the adjusted settings were applied to all of 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 also 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.

2.1.2 Pre-processing

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

2.1.3 Post-processing

Fugro has developed a unique method for processing lidar data.

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

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

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

2.1.4 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.

2.1.4.1 Raw Point Cloud Data

All collected flight lines were included in generating this product, after boresight was completed and the adjustment was made to match the data to the ground control. The flight lines went through the following processes: 1) Assign flight line ID to each point and file source ID to each flight line based upon the flight line trajectory; 2) Re-project flight lines files to deliverable projection/datum and unit; 3) Package final LAS 1.4 format deliverable and QC.

The raw point cloud data was delivered in fully compliant LAS v1.4, Point Record Format 6 with Adjusted Standard GPS Time. The flight lines include all collected points and were fully calibrated, georeferenced, and adjusted to ground. Correct and properly formatted georeference information as Open Geospatial Consortium (OGC) well known text (WKT) was assigned in all LAS file headers. Intensity values are included for each point, normalized to 16-bit. This deliverable was organized and delivered in their original swath, one file per swath, one swath per file.

2.1.4.2 Classified Point Cloud Data

Once manual inspection, QC and final autofilter 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 in the following spatial reference system: UTM Zone 13, 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. Water points were classified to Class 9 and Ignored ground points were classified to Class 20 using the collected hydro breaklines.

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
(06) Class 6 - Buildings
(07) Class 7 – Low Noise
(08) Class 8 – Model Key Point
(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.

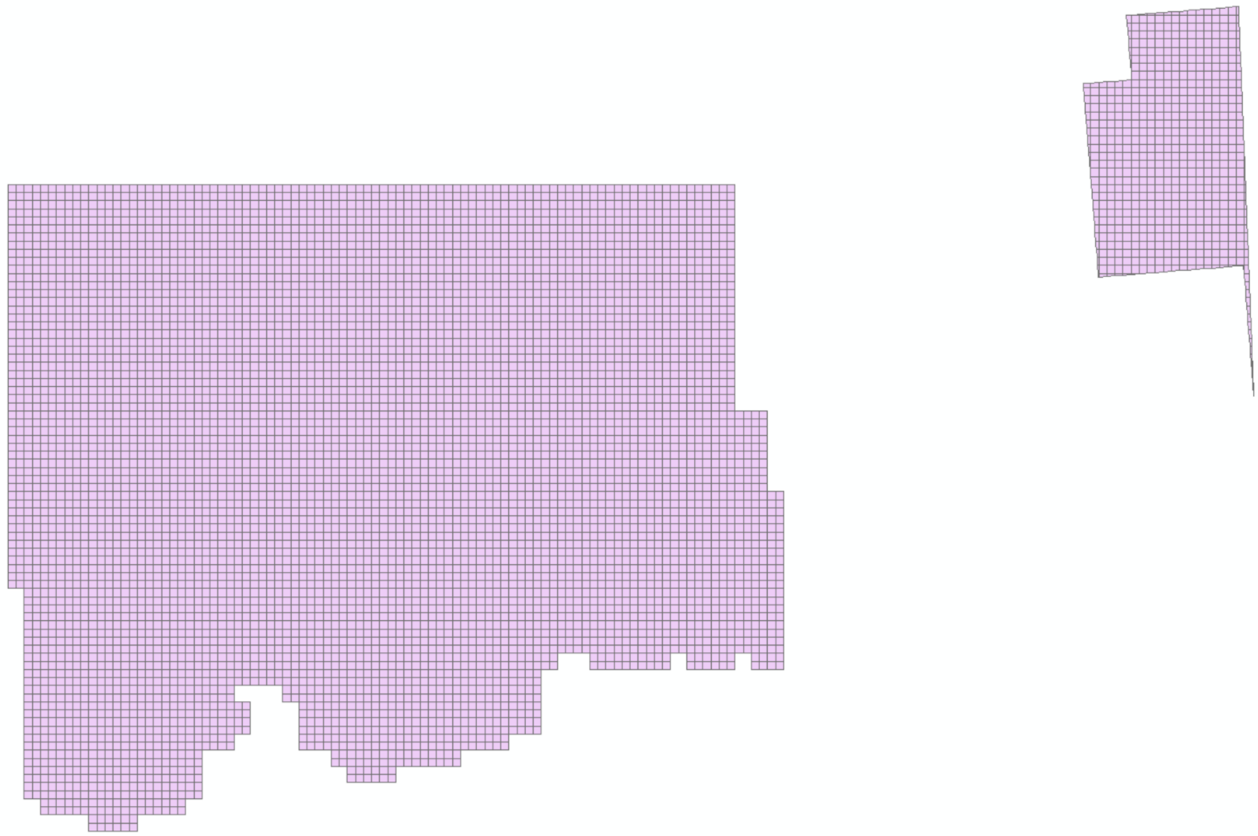

Figure 2: Delivery Block Tiles

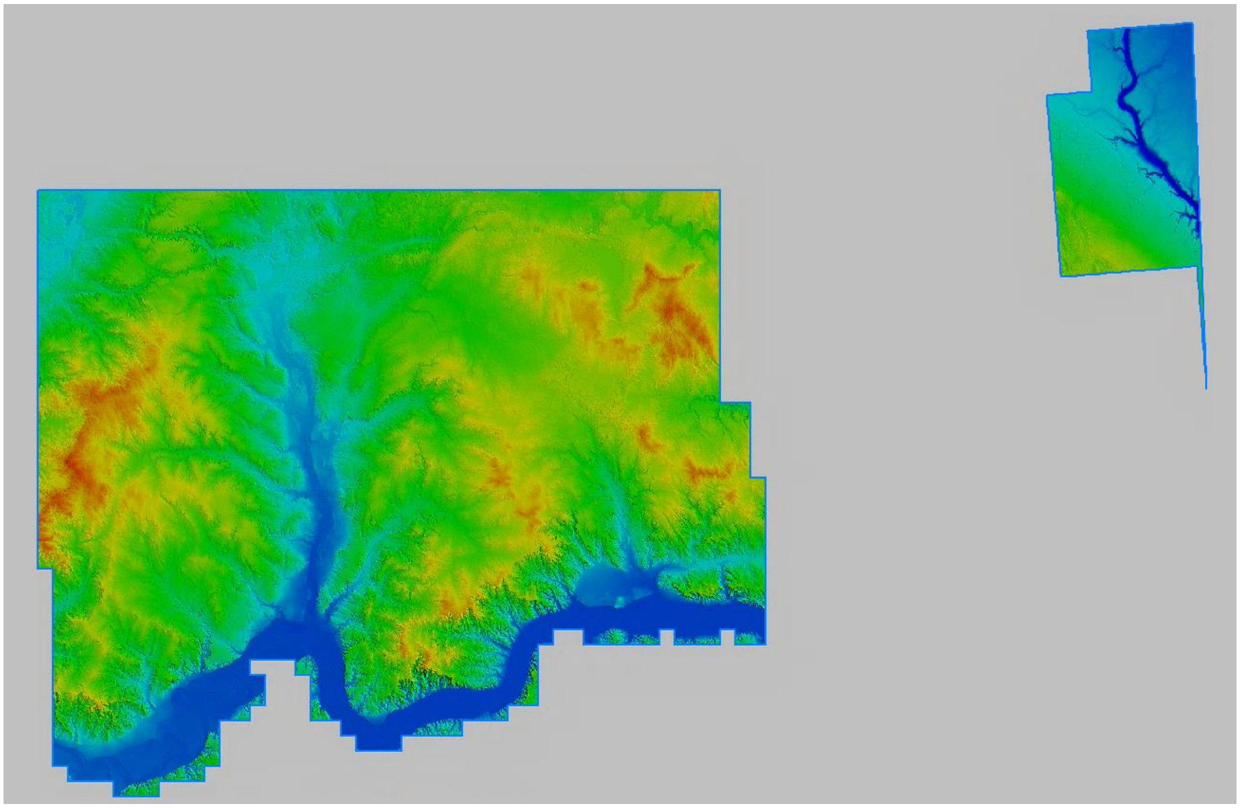

Figure 3: Block 4 Shaded Relief

2.1.4.3 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 1 meter. Where needed, supplemental breaklines were collected and used in DEM generation under the bridges to ensure a logical terrain surface below a bridge. This was delivered as a separate shapefile and delivered with the hydro product.

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 for the production of the lidar-derived hydro flattened bare earth DEM surface in initial grid format at 1 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 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 TIF 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.

2.1.5 Lidar Hydro Breakline Collection

Hydro linework is produced by heads-up digitizing using classified lidar datasets. 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.

3. 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.

3.1 Positional Accuracy

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

3.2 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 table 1 below for the achieved accuracies within this AOI. The raw swath point cloud data met the required accuracy levels before point cloud classification and derivative product generation.

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 3 and 4 below for the achieved accuracies within Block 4 AOI.

Table 3: Accuracy of the classified point cloud (Block 4)

LAS	RMSEz (non-vegetated)	NVA at 95-percent confidence level	VVA at 95th percentiles
Specification (cm)	≤ 10	≤ 19.6	≤ 29.4
Calculated Values (cm)	3.1	6.0	9.0
Specification (m)	≤ 0.100	≤ 0.196	≤ 0.294
Calculated Values (m)	0.031	0.06	0.09
Number of points	66	66	48

Table 4: Accuracy of the Derived DEM (Block 4)

DEM	RMSEz (non-vegetated)	NVA at 95-percent confidence level	VVA at 95th percentiles
Specification (cm)	≤ 10	≤ 19.6	≤ 29.4
Calculated Values (cm)	3.3	6.5	9.8
Specification (m)	≤ 0.100	≤ 0.196	≤ 0.294
Calculated Values (m)	0.033	0.065	0.098
Number of points	66	66	48

3.3 Relative Accuracy

Swath Separation Rasters are created at 2m resolution using 8cm threshold to show how the individual flightlines agree to one another in areas of overlap. 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).

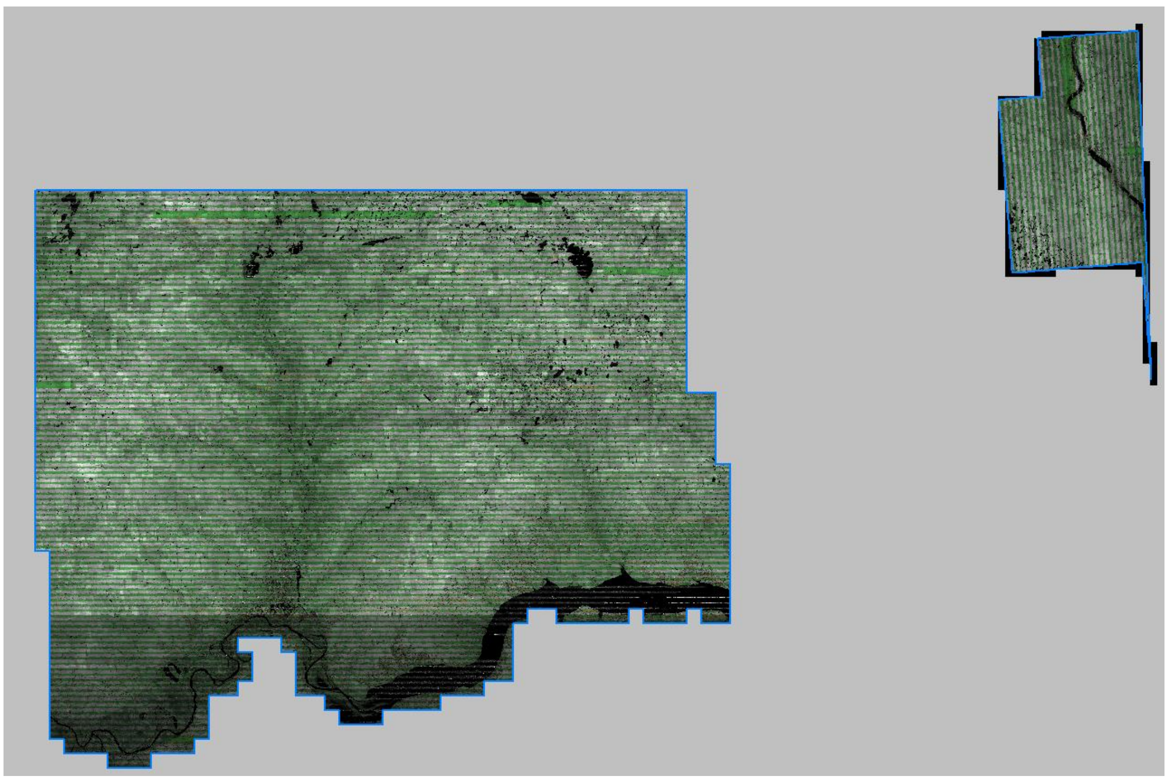

Figure 4: Swath Separation

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.

Because this project was originally collected and processed under a different scope, flight line overlap points weren't classified following the USGS's lidar Base Specification. They were originally classified as Class 11 which include some noise points. When converting the existing data to the USGS specification, Fugro proposed an alternative solution for handling the flight line overlap point with the intent of controlling costs to the USGS. Reclassifying the flight line overlap points to the USGS standard classes would be labor intensive and would increase overall project costs substantially. Fugro's alternative solution transferred all flightline overlap points to Withheld Class 1 while keeping other noise points in Withheld 7 and Withheld 18 for differentiation. Therefore, Withheld Class 1 points were included in the generation of the swath separation images to demonstrate the relative accuracy achieved.