Dewberry

PROJECT REPORT

For the

U.S. Corp of Engineers High Resolution LiDAR Data Acquisition & Processing for portions of Connecticut

USACE Contract:

W912P9-10-D-0534

Task Order Number:

0002

Prepared for:
USDANRCS

Prepared by:
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Report Date: September 8, 2011

Table of Contents

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 use by USDA-NRCS Connecticut in such projects as conservation planning, floodplain mapping, dam safety assessments, and hydrologic modeling.

The LiDAR data were processed to a bare-earth digital elevation model (DEM). Detailed breaklines, bare-earth DEMs, and multiple LiDAR derivatives were produced for the project area. Data was formatted according to tiles with each tile covering an area of 1000 m by 1000 m. A total of 4,840 tiles were produced for the project encompassing an area of approximately 4,589 sq. kilometers.

The Project Team

Dewberry served as the prime contractor for the project. In addition to project management, Dewberry was responsible for LAS classification, all LiDAR products, breakline production, Digital Elevation Model (DEM) production, and quality assurance.

Dewberry's IES offices completed ground surveying for the project and delivered surveyed checkpoints. Their task was to acquire surveyed checkpoints for the project to use in independent testing of the vertical accuracy of the LiDAR-derived surface model. They also verified the GPS base station coordinates used during LiDAR data acquisition to ensure that the base station coordinates were accurate. Note that a separate Survey Report was created for this portion of the project.

Earth Eye completed LiDAR data acquisition and data calibration for the project area.

Survey Area

The project area addressed by this report covers all of the Connecticut counties of Tolland and Windham and portions of the Connecticut counties of Hartford, Middlesex, and New London.

Date of Survey

The LiDAR aerial acquisition was conducted from November 3, 2010 thru December 11, 2010.

Datum Reference

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

Horizontal Datum: The horizontal datum for the project is North American Datum of 1983 (NAD 83)
Vertical Datum: The Vertical datum for the project is North American Vertical Datum of 1988 (NAVD88)
Coordinate System: UTM Zone 18N
Units: Horizontal units are in meters, Vertical units are in meters.
Geiod Model: Geoid09 (Geoid 09 was used to convert ellipsoid heights to orthometric heights).

LiDAR Vertical Accuracy

For the Connecticut LiDAR Project, the tested $RMSE_z$ for open terrain checkpoints equaled **0.05 m** compared with the 0.0925 m specification; and the FVA computed using $RMSE_z$ x 1.9600 was equal to **0.09 m**, compared with the 0.185 m specification.

For the Connecticut LiDAR Project, the tested CVA computed using the 95th percentile was equal to **0.17 m,** compared with the 0.185 m specification.

Project Deliverables

The deliverables for the project are listed below.

1. Classified Point Cloud LiDAR Data (Tiled)
2. Bare Earth LiDAR Data (Tiled)
3. First Return LiDAR Data (Tiled)
4. Last Return LiDAR Data (Tiled)
5. Model Key Point LiDAR Data (Tiled)
6. Bare Earth Surface (Raster DEM – GRID Format)
7. Control & Accuracy Checkpoint Report & Points
8. Metadata
9. Project Report (Acquisition, Processing, QC)
10. Project Extents
11. Breakline Data (File GDB)
12. Intensity Imagery (GeoTIFF Format with 0.3 m pixels)

1 Project Tiling Footprint

Four thousand eight hundred and forty (4,840) tiles were delivered for the project. Each tile's extent is 1000 meters by 1000 meters.

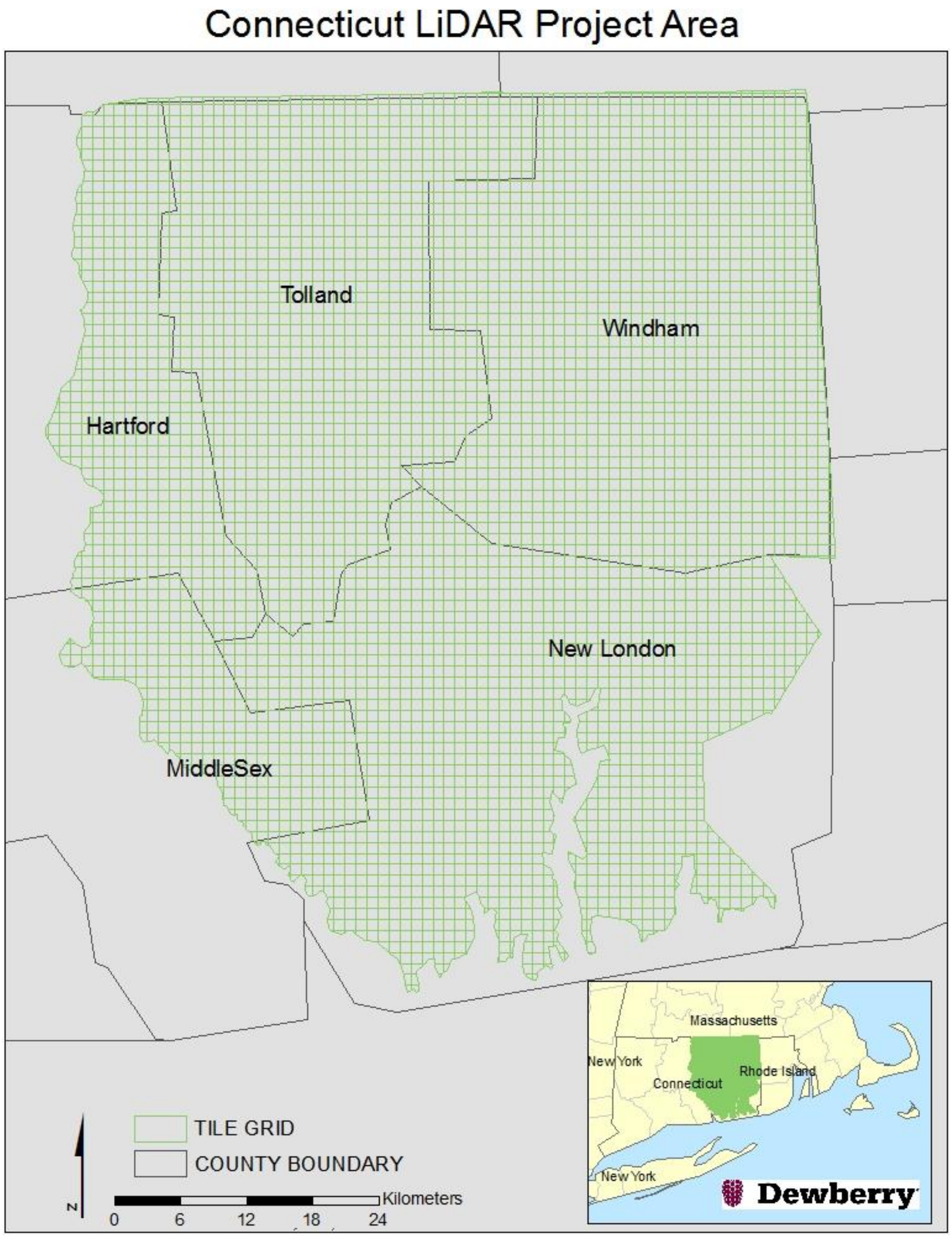

Figure 1: Project Map

1.1 List of delivered tiles (4,840):

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18TBG6324	18TBG6415	18TBG6505	18TBG6552
18TBG6325	18TBG6416	18TBG6506	18TBG6553
18TBG6326	18TBG6417	18TBG6507	18TBG6554
18TBG6327	18TBG6418	18TBG6508	18TBG6555
18TBG6328	18TBG6419	18TBG6509	18TBG6556
18TBG6329	18TBG6420	18TBG6514	18TBG6607
18TBG6330	18TBG6421	18TBG6515	18TBG6608
18TBG6331	18TBG6422	18TBG6516	18TBG6614

18TBG6615
18TBG6616
18TBG6617
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18TBG6723
18TBG6724

2 LiDAR Acquisition Report

2.1 PROJECT DESCRIPTION

The project area for included approximately 1741 contiguous square miles for portions of Connecticut including a buffer of 200 meters. LiDAR sensor data were collected with the Leica ALS60 sn146. No imagery was requested or delivered. The data was delivered in the UTM coordinate system, meters, zone 18, horizontal datum NAD83, vertical datum NGVD88, Geoid 09. Deliverables for the project included a raw (unclassified) calibrated LiDAR point cloud, survey control, and a final control report.

2.2 MISSION PLANNING

GPS Base Stations

Flight planning constrained all GPS baselines to a maximum of 25 miles. Three GPS base stations were required as shown.

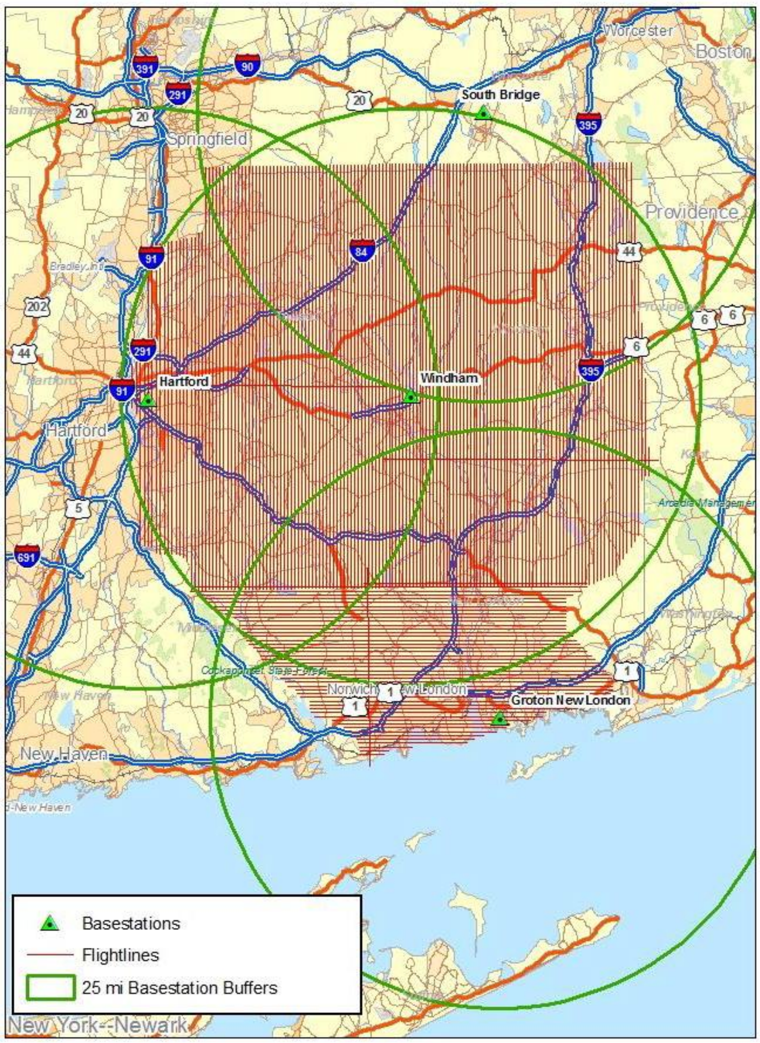


Figure 2: GPS Stations

LiDAR Flight Plan
LiDAR was flown based on the following sensor parameters and flight plan to achieve maximum efficiency and nominal pulse densities.

SENSOR PARAMETERS ALS 60 Sensor Parameters	
Flight Hours	56.4
Pulse Rate	117,900
Field of View	32 degrees
Side Lap	50%
Average Density	2 ppm

Table 1: Sensor Parameters

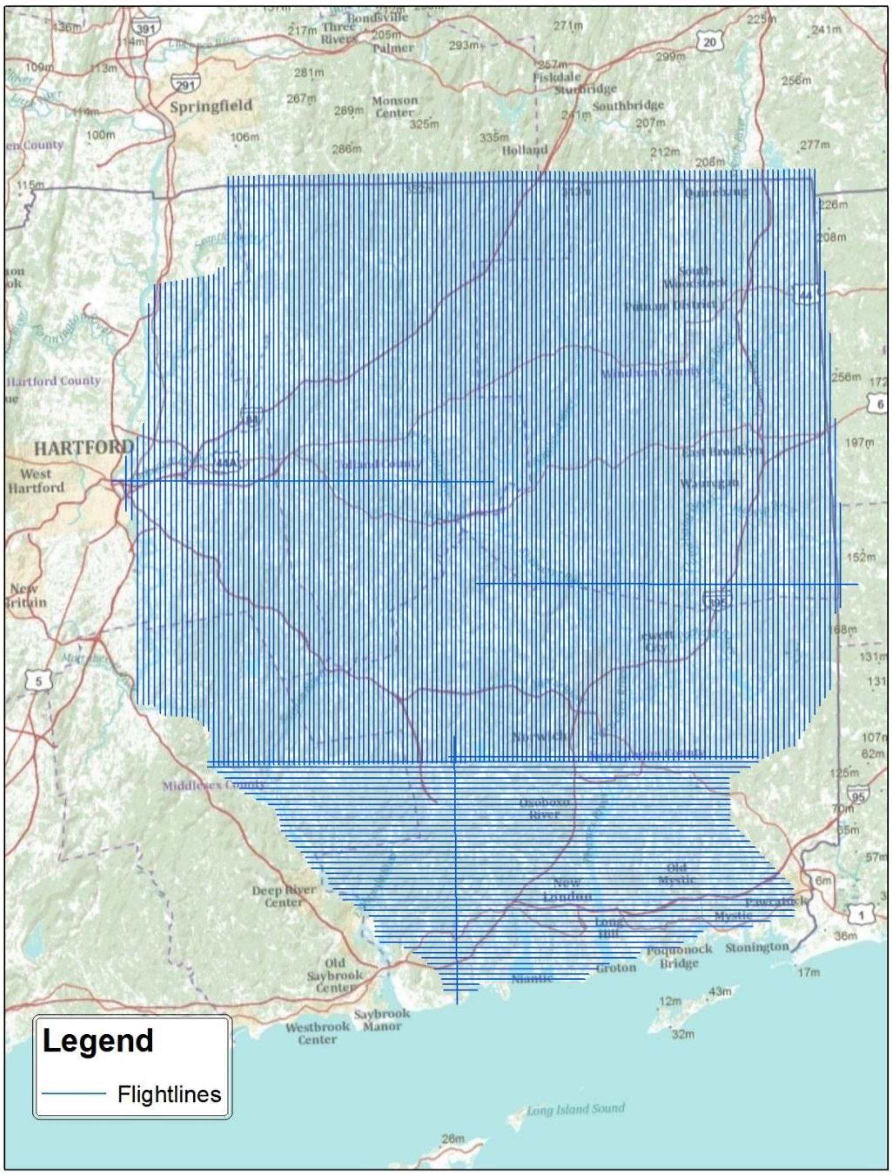


Figure 3: Flight Layout

CONTROL LAYOUT

A total of 39 distributed control points were planned and collected with static GPS observations as shown.

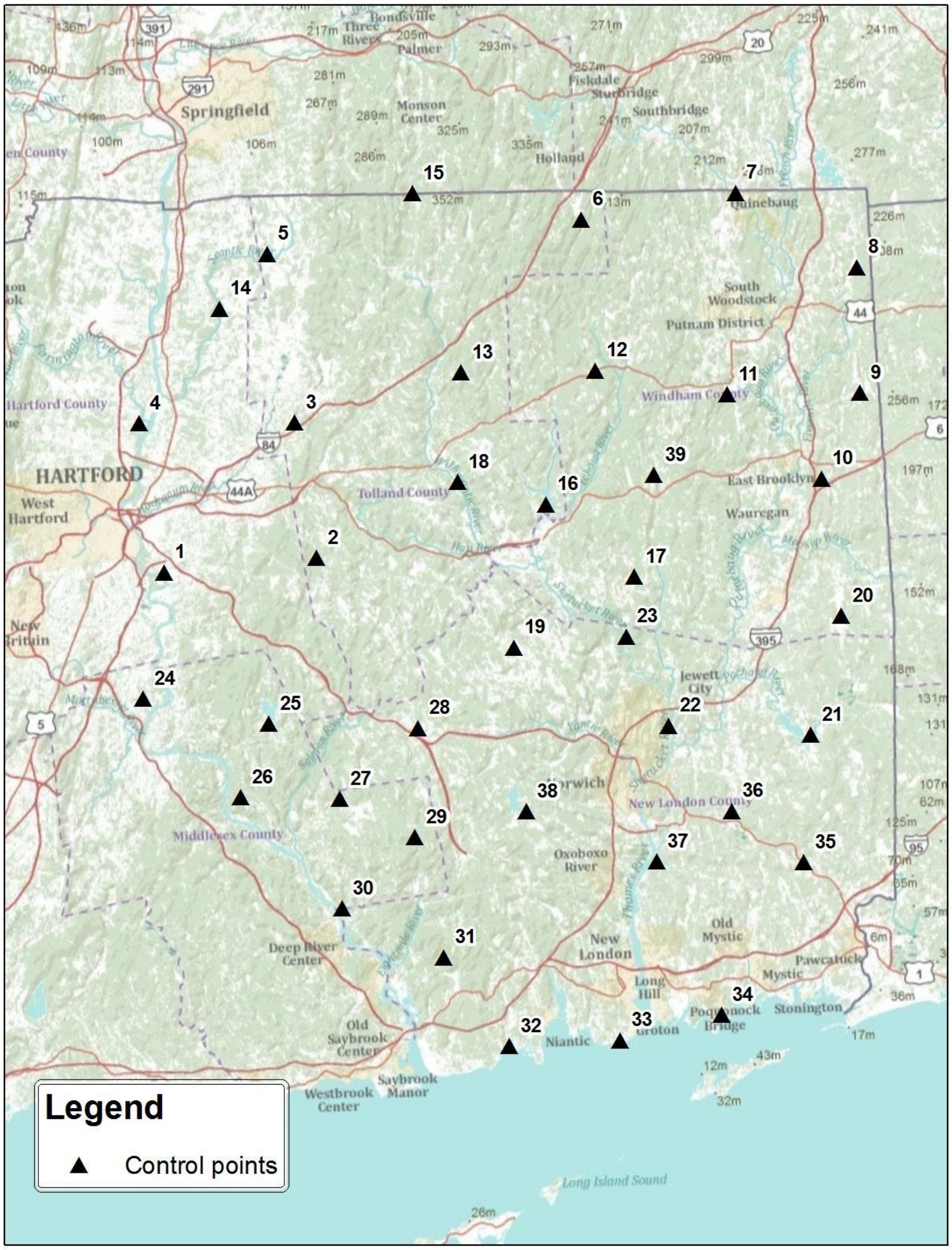


Figure 4: Control Points

2.3 ACQUISITION

Airborne LiDAR

Notice to proceed was received from Dewberry on November 2, 2010. Data were acquired between November 3 through December 11, 2010 including necessary patch flight lines due to gaps or other anomalies. All data was reviewed at the Earth Eye Orlando Corporate office prior to departing the project location. Following is the flight acquisition summary:

Connecticut Progress Report			
Date	Weather Conditions	Missions Complete	Lines Flown
11/3/2010	Clear, medium strength winds	1	15
11/4/2010	Clouds with rain	0	0
11/5/2010	Cloudy	0	0
11/6/2010	scattered clouds, light wind	1	5
11/7/2010	Cloudy and rainy	0	0
11/8/2010	Cloudy and rainy	0	0
11/9/2010	Very cloudy	0	0
11/10/2010	Clear, very strong winds	1	8
11/11/2010	Clear, high winds	2	17
11/12/2010	Clear, moderate winds	2	15
11/13/2010	Clear, light winds	2	14
11/14/2010	Clear in the morning, clouds in afternoon,light winds	2	14
11/15/2010	Very cloudy	0	0
11/16/2010	Overcast at 3000 all day, plane maintenance	0	0
11/17/2010	Cloudy, plane Maintenance	0	0
11/18/2010	Cloudy at 5000	0	0
11/19/2010	Clear in the AM and Evening, cloudy afternoon	2	13
11/20/2010	Cloudy and strong winds (60kt)	0	0
11/21/2010	Clear with moderate winds	2	14
11/22/2010	Overcast at 2000ft	0	0
11/23/2010	Overcast at 5500ft	0	0
11/24/2010	Thanksgiving Break	0	0
11/25/2010	Thanksgiving Break	0	0
11/26/2010	Thanksgiving Break	0	0
11/27/2010	Thanksgiving Break	0	0
11/28/2010	Clear until afternoon, moderate winds	2	12
11/29/2010	Clear, calm winds	2	19
11/30/2010	Overcast at 1500ft	0	0
12/1/2010	Rain all day, extreme winds (60kt)	0	0
12/2/2010	Plane repairs (cylinder, prop)	0	0
12/3/2010	Ceiling at 4000ft, Plane repairs	0	0
12/4/2010	Very cloudy, Plane repairs	0	0
12/5/2010	Very cloudy, Plane repairs	0	0
12/6/2010	Very cloudy,Snow, Plane repairs	0	0
12/7/2010	Very cloudy	0	0
12/8/2010	Mostly cloudy @ 4500	0	0
12/9/2010	Late PM clear	2	28
12/10/2010	Early AM clear	2	18
12/11/2010	Clear, moderate winds	1	18

Table 2: Flight acquisition summary

Survey Control

Compliance with the accuracy standard was ensured through the collection of GPS ground control during the acquisition of aerial LiDAR and the establishment of a GPS base station operating at the airport. In addition to the base stations, CORS bases may have been used to supplement the solutions. The following criteria were adhered to during control point collection.

1. Each point was collected during periods of very low (<2) DOP.
2. No point was collected with a base line greater than 25 miles.
3. Each point was collected at a place of constant slope so as to minimize any errors introduced through LiDAR triangulation.
4. Each point was collected at moderate intensity surfaces so any intensity based anomalies could be avoided.

Note: The base station equipment used was a Trimble R7 with a zephyr geodetic model 2 antenna. The control points were collected with a Trimble R8 integrated receiver and antenna unit.
The control points utilized in data calibration and final accuracy assessment are as follows:

Point	X	Y	Z	Point	X	Y	Z
1	698093.01	4620835.64	8.84	21	759605.76	4605458.34	57.68
2	712590.80	4622232.26	163.83	22	746088.54	4606301.79	24.38
3	710524.55	4635055.93	119.80	23	742032.43	4614771.09	60.89
5	707898.94	4651075.36	59.29	24	696119.06	4608862.22	35.85
6	737774.65	4654321.29	215.12	25	708106.81	4606499.07	147.70
7	752428.44	4656847.55	111.19	26	705422.94	4599507.38	101.18
8	763983.27	4649796.16	123.44	27	714792.36	4599359.27	114.11
9	764234.20	4637894.84	179.23	28	722282.65	4606086.88	138.36
10	760611.62	4629755.04	110.96	29	721957.94	4595715.82	57.27
11	751618.82	4637723.72	92.70	30	715010.96	4588961.02	51.45
12	739099.68	4640006.75	209.42	31	724712.15	4584349.10	25.72
13	726349.39	4639827.59	210.04	32	730943.52	4575898.81	3.47
14	703386.22	4645858.32	15.47	33	741491.25	4576469.44	9.96
15	721719.06	4656824.04	191.39	34	751096.36	4578878.13	2.55
16	734421.94	4627325.81	81.17	36	752082.50	4598222.32	37.51
17	742843.25	4620456.27	85.13	37	744933.08	4593442.87	13.99
18	726004.54	4629441.06	83.19	38	732552.33	4598193.97	123.31
19	731355.30	4613723.70	119.69	39	744701.83	4630089.18	203.25
20	762486.95	4616742.19	192.81				
UTM coordinate system, meters, zone 18							
horizontal datum NAD83, vertical datum NGVD88, Geoid 09							

Table 3: Control points and accuracy assesment

2.4 PROCESSING

LiDAR Calibration

The calibration process considered all errors inherent with the equipment including errors in GPS, IMU, and sensor specific parameters. Adjustments were made to achieve a flight line to flight line data match (relative calibration) and subsequently adjusted to control for absolute accuracy. Process steps to achieve this are as follows:

1. Rigorous LiDAR calibration: all sources of error such as the sensor's ranging and torsion parameters, atmospheric variables, GPS conditions, and IMU offsets were analyzed and removed to the highest level possible. This method addresses all errors, both vertical and horizontal in nature. Ranging, atmospheric variables, and GPS conditions affect the vertical position of the surface, whereas IMU offsets and torsion parameters affect the data horizontally. The horizontal accuracy is proven through repeatability: when the position of features remains constant no matter what direction the plane was flying and no matter where the feature is positioned within the swath, relative horizontal accuracy is achieved.
2. Absolute horizontal accuracy is achieved through the use of differential GPS with base lines shorter than 25 miles. The base station is set at a temporary monument that is 'tied-in' to the CORS network. The same position is used for every lift, ensuring that any errors in its position will affect all data equally and can therefore be removed equally.

3. Vertical accuracy is achieved through the adjustment to ground control survey points within the finished product. Although the base station has absolute vertical accuracy, adjustments to sensor parameters introduces vertical error that must be normalized in the final (mean) adjustment.
The minimum expected horizontal accuracy was tested during the boresight process to meet or exceed the National Standard for Spatial Data Accuracy (NSSDA) for a Horizontal accuracy of 1 meter RMSE or better and a Vertical Accuracy of RMSE(z) ≤ 9.25 cm

2.5 QA/QC

Once all lifts are horizontally and vertically calibrated a final vertical accuracy check against the control is performed. The result is analyzed against the project specified accuracy to make sure it meets the requirement. The final accuracy for this project yielded a **0.0344 meter RMSEz @ 95% confidence level**. Following are list of all control points compared to the final calibrated LiDAR surface.

Point	X	Y	Z	Z TIN	Delta
1	698093.005	4620835.643	8.84	8.8523	-0.0123
2	712590.804	4622232.256	163.83	163.8549	-0.0249
3	710524.547	4635055.934	119.8	119.7854	0.0146
5	707898.944	4651075.358	59.29	59.3159	-0.0259
6	737774.654	4654321.285	215.12	215.1237	-0.0037
7	752428.436	4656847.551	111.19	111.1021	0.0879
8	763983.273	4649796.155	123.44	123.4035	0.0365
9	764234.196	4637894.84	179.23	179.1865	0.0435
10	760611.615	4629755.038	110.96	110.9119	0.0481
11	751618.822	4637723.715	92.7	92.7003	-0.0003
12	739099.676	4640006.745	209.42	209.3916	0.0284
13	726349.389	4639827.593	210.04	210.0474	-0.0074
14	703386.222	4645858.318	15.47	15.4295	0.0405
15	721719.062	4656824.044	191.39	191.3346	0.0554
16	734421.939	4627325.814	81.17	81.1282	0.0418
17	742843.251	4620456.271	85.13	85.0947	0.0353
18	726004.538	4629441.058	83.19	83.169	0.021
19	731355.301	4613723.695	119.69	119.6775	0.0125
20	762486.953	4616742.187	192.81	192.8352	-0.0252
21	759605.757	4605458.336	57.68	57.6962	-0.0162
22	746088.535	4606301.792	24.38	24.3109	0.0691
23	742032.43	4614771.088	60.89	60.8836	0.0064
24	696119.056	4608862.22	35.85	35.8347	0.0153
25	708106.805	4606499.071	147.7	147.7071	-0.0071
26	705422.943	4599507.381	101.18	101.1703	0.0097
27	714792.356	4599359.266	114.11	114.1564	-0.0464
28	722282.649	4606086.879	138.36	138.3688	-0.0088
29	721957.936	4595715.818	57.27	57.2781	-0.0081
30	715010.96	4588961.024	51.45	51.4595	-0.0095
31	724712.146	4584349.095	25.72	25.7126	0.0074
32	730943.521	4575898.813	3.47	3.5196	-0.0496
33	741491.247	4576469.438	9.96	9.9411	0.0189
34	751096.36	4578878.132	2.55	2.6215	-0.0715
36	752082.503	4598222.32	37.51	37.4741	0.0359
37	744933.082	4593442.871	13.99	14.0281	-0.0381
38	732552.334	4598193.97	123.31	123.2907	0.0193
39	744701.83	4630089.179	203.25	203.2495	0.0005

Final Accuracy	
Mean	-0.0079
RMSE	0.0344

Table 4: Final accuracy

2.6 Final Deliverables

Final project deliverables:

1. Calibrated raw (unclassified) LiDAR point clouds by flight line in las format
2. Survey Control points in excel format
3. Survey control accuracy report in excel format
4. Final Report PDF

Projections/Datums

UTM coordinate system, meters, zone 18, horizontal datum NAD83, vertical datum NGVD88, Geoid 09

3 LiDAR Processing & Qualitative Assessment

3.1 Data Classification and Editing

Earth Eye delivered LiDAR swaths to Dewberry that were calibrated and projected to project specifications. Dewberry processed the data using GeoCue and TerraScan software. The initial step is the setup of the GeoCue project, which is done by importing a project defined tile boundary index encompassing the entire project area. The acquired 3D laser point clouds, in LAS binary format, were imported into the GeoCue project and tiled according to the project tile grid. Once tiled, the laser points were classified using a proprietary routine in TerraScan. This routine removes any obvious outliers from the dataset following which the ground layer is extracted from the point cloud. The ground extraction process encompassed in this routine takes place by building an iterative surface model.

This surface model is generated using three main parameters: building size, iteration angle and iteration distance. The initial model is based on low points being selected by a "roaming window" with the assumption is that these are the ground points. The size of this roaming window is determined by the building size parameter. The low points are triangulated and the remaining points are evaluated and subsequently added to the model if they meet the iteration angle and distance constraints. This process is repeated until no additional points are added within iterations. A second critical parameter is the maximum terrain angle constraint, which determines the maximum terrain angle allowed within the classification model.

Once the initial ground routine has been performed on the data, Dewberry creates Delta Z (DZ) orthos to check the relative accuracy of the LiDAR data. These orthos compare the elevations of LiDAR points from overlapping flight lines on a 1 meter pixel cell size basis. If the elevations of points within each pixel are within 10 cm of each other, the pixel is colored green. If the elevations of points within each pixel are between 10 cm and 20 cm of each other, the pixel is colored yellow, and if the elevations of points within each pixel are greater than 20 cm in difference, the pixel is colored red. Pixels that do not contain points from overlapping flight lines are colored according to their intensity values. DZ orthos can be created using the full point cloud or ground only points and are used to review and verify the calibration of the data is acceptable. Some areas are expected to show sections or portions of red, including terrain variations, slope changes, and vegetated areas or buildings if the full point cloud is used. However, large or continuous sections of yellow or red pixels can indicate the data was not calibrated correctly or that there were issues during acquisition that could affect the usability of the data. The DZ orthos for Connecticut showed that the data was calibrated correctly with no issues that would affect its usability. The figure below shows an example of the DZ orthos.

Figure 5: DZ orthos created from ground only points. Some red pixels are visible along embankments and sloped terrain, as expected. Open, flat areas are green indicating the calibration and relative accuracy of the data is acceptable.

Dewberry utilizes a variety of software suites for data processing. After the initial ground classification, 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 employ 3D visualization techniques to view the point cloud at multiple angles and in profile to ensure that non-ground points are removed from the ground classification. After the ground classification corrections were completed, the dataset was processed through a water classification routine that utilizes breaklines compiled by Dewberry to automatically classify hydro features. The water classification routine selects ground points within the breakline polygons and re-classifies them as class 9, water.

Terrascan was also used to create model key points. An algorithm is defined that intelligently thins bare earth ground points so that points necessary to define breaks and elevation changes in the terrain are kept while unnecessary or redundant points are not included in the model key points. The model key points are then written to its own file, according to the project tile grid, with all points located in class 8. There were three files that did not contain enough model key points to create a file. The tiles that do not have corresponding model key points are:

- 18TXM9909
- 18TYM0056
- 18TYL4496

GeoCue was used to create the bare earth only LiDAR tiles, first return only LiDAR tiles, and last return only LiDAR tiles. For bare earth only LiDAR tiles, class 2 points are filtered from the full point cloud data and written to its own file, according to the project tile grid. There was one file that did not contain enough bare earth points to create a file. The tile that does not have corresponding bare earth points is:

- 18TYM0056

For first return and last return tiles, the desired echo return is filtered from the full point cloud and written to its own file, according to the project tile grid. The first return and last return files include the desired return from all classes. The points for these files are located in class 1. There was one file that did not contain enough first return or last return point to create a file. The tile that does not have corresponding first return or last return points is:

- 18TYM0056

After all processing and classification has been completed, GeoCue software is used to update the LAS version, projection information, creation day, and creation year of every LiDAR file.

3.2 Qualitative Assessment

Dewberry qualitative assessment utilizes a combination of statistical analysis and interpretative methodology to assess the quality of the data for a bare-earth digital elevation model (DEM). This process looks for anomalies in the data and also identifies areas where man-made structures or vegetation points may not have been classified properly to produce a bare-earth model.

Within this review of the LiDAR data, two fundamental questions were addressed:

- Did the LiDAR system perform to specifications?
- Did the vegetation removal process yield desirable results for the intended bare-earth terrain product?

Mapping standards today address the quality of data by quantitative methods. If the data are tested and found to be within the desired accuracy standard, then the data set is typically accepted. Now with the proliferation of LiDAR, new issues arise due to the vast amount of data. Unlike photogrammetrically-derived DEMs where point spacing can be eight meters or more, LiDAR nominal point spacing for this project is 1 point per 0.7 square meters. The end result is that millions of elevation points are measured to a level of accuracy previously unseen for traditional elevation mapping technologies and vegetated areas are measured that would be nearly impossible to survey by other means. The downside is that with millions of points, the dataset is statistically bound to have some errors both in the measurement process and in the artifact removal process.

As previously stated, the quantitative analysis addresses the quality of the data based on absolute accuracy. This accuracy is directly tied to the comparison of the discreet measurement of the survey checkpoints and that of the interpolated value within the three closest LiDAR points that constitute the vertices of a three-dimensional triangular face of the TIN. Therefore, the end result is that only a small sample of the LiDAR data is actually tested. However there is an increased level of confidence with LiDAR data due to the relative accuracy. This relative accuracy is based on how well one LiDAR point "fits" in comparison to the next contiguous LiDAR measurement, and is verified with DZ orthos . Once the absolute and relative accuracy has been ascertained, the next stage is to address the cleanliness of the data for a bare-earth DEM.

By using survey checkpoints to compare the data, the absolute accuracy is verified, but this also allows us to understand if the artifact removal process was performed correctly. To reiterate the quantitative approach, if the LiDAR sensor operated correctly over open terrain areas, then it most likely operated correctly over the vegetated areas. This does not mean that the entire bare-earth was measured; only that the elevations surveyed are most likely accurate (including elevations of treetops, rooftops, etc.). In the event that the LiDAR pulse filtered through the vegetation and was able to measure the true surface (as well as measurements on the surrounding vegetation) then the level of accuracy of the vegetation removal process can be tested as a by-product.

To fully address the data for overall accuracy and quality, the level of cleanliness (or removal of above-ground artifacts) is paramount. Since there are currently no effective automated testing procedures to measure cleanliness, Dewberry employs a combination of statistical and visualization processes. This includes creating pseudo image products such as LiDAR orthos produced from the intensity returns, Triangulated Irregular Network (TIN)'s, Digital Elevation Models (DEM) and 3-dimensional models. By creating multiple images and using overlay techniques, not only can potential errors be found, but Dewberry can also find where the data meets and exceeds expectations. This report will present representative examples where the LiDAR and post processing had issues as well as examples of where the LiDAR performed well.

Dewberry utilizes GeoCue software as the primary geospatial process management system. GeoCue is a three tier, multi-user architecture that uses .NET technology from Microsoft. .NET technology provides the real-time notification system that updates users with real-time project status, regardless of who makes changes to project entities. GeoCue uses database technology for sorting project metadata. Dewberry uses Microsoft SQL Server as the database of choice. Specific analysis is conducted in Terrascan and QT Modeler environments.

Following the completion of LiDAR point classification, the Dewberry qualitative assessment process flow for the Connecticut LiDAR project incorporated the following reviews:

1. *Format:* The LAS files are verified to meet project specifications. The LAS files conform to the specifications outlined below.

- Format, Echos, Intensity
    - LAS format 1.2, point data record format 1
    - Point data record format 1
    - Multiple returns (echos) per pulse
    - Intensity values populated for each point
- ASPRS classification scheme
    - Class 1 – unclassified
    - Class 2 – ground
    - Class 7 – Noise
    - Class 9 – Water
- Projection
    - Datum – North American Datum 1983
    - Projected Coordinate System –UTM Zone 18N
    - Units – Meters
    - Vertical Datum – North American Vertical Datum 1988, Geoid 09

        - Vertical Units - Meters
    - LAS header information:
        - Class (Integer)
        - GPS Week Time (0.0001 seconds)
        - Easting (0.01 foot)
        - Northing (0.01 foot)
        - Elevation (0.01 foot)
        - Echo Number (Integer 1 to 4)
        - Echo (Integer 1 to 4)
        - Intensity (8 bit integer)
        - Flight Line (Integer)
        - Scan Angle (Integer degree)

2. *Data density, data voids:* The LAS files are used to produce Digital Elevation Models using the commercial software package "QT Modeler" which creates a 3-dimensional data model derived from Class 2 (ground points) in the LAS files. Grid spacing is based on the project density deliverable requirement for un-obscured areas. For the Connecticut LiDAR project it is stipulated that the minimum post spacing in un-obscured areas should be 1 point per 0.7 square meter.

    a. The Connecticut LiDAR data has full coverage. Only acceptable voids (areas with no LiDAR returns in the LAS files) are present in the LiDAR, including voids caused by bodies of water.

3. *Bare earth quality:* Dewberry reviewed the cleanliness of the bare earth to ensure the ground has correct definition, meets the project requirements, there is correct classification of points, and there are less than 5% residual artifacts.
    a. *Building Removal:* Large buildings, unique construction, and buildings built on sloped terrain or built into the ground can make a noticeable impact on the bare earth DEM once they have been removed, often in the form of large void areas with obvious triangulation or interpolation across the area and general lack of detail in the ground where the structure stood. Dewberry analysts verified that structures have been removed from the ground, that areas along slopes missing definition are due to structural or vegetation removal and not aggressive classification, and that holes or removal of ground is accurate. The figure below shows a unique structure in Connecticut that was partially built into the ground. While the DEM has noticeable "holes" and tinning across an embankment (Figure 7), the profile shows that these features are caused by the structure removal process and are correct (Figure 8).

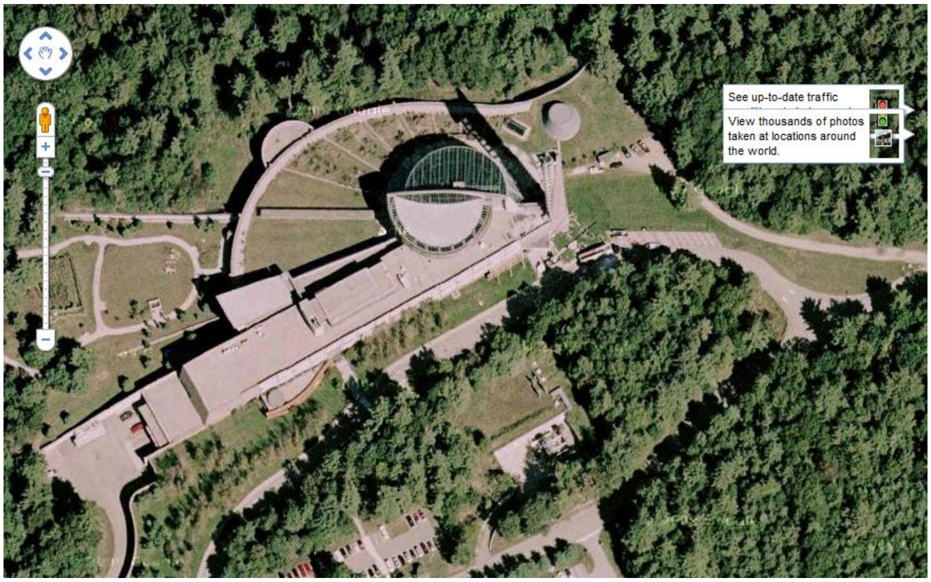


Figure 6: Google Earth image of unique structure in tile 18TBF5394.

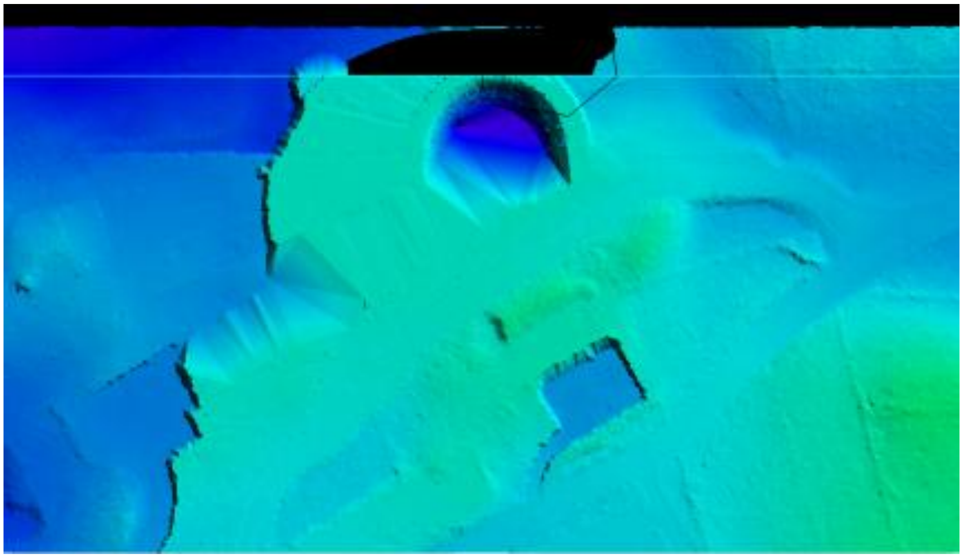


Figure 7: DEM of tile 18TBF5394. There are some large "holes" and loss of detail along the embankment on the western side of the tile that are noticeable in the DEM.

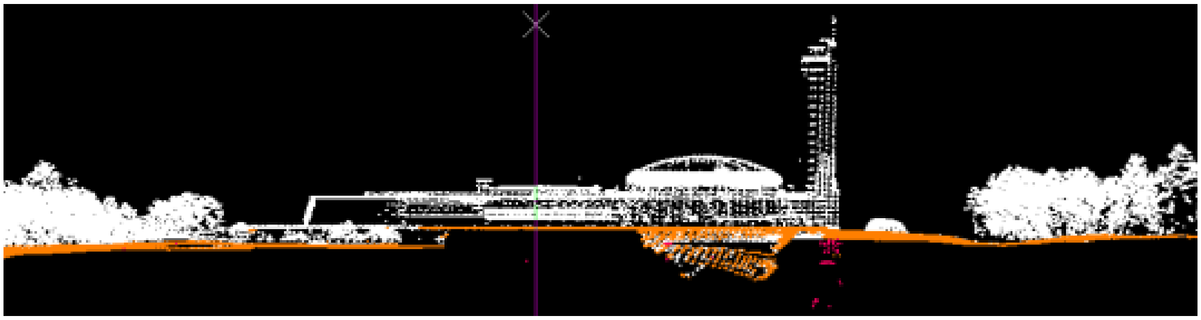


Figure 8: Profile of structure identified in tile 18TBF5394. Unclassified points are white, ground points are orange, and low noise points are red. The profile shows that the domed feature is partly built below ground

in some areas and the loss of detail along the western embankment is due to the structure being built over the embankment. The DEM surface is correct.

b. *Hydraulic Structures:* There are hydraulic structures located on water ways and hydrologic features throughout the Connecticut project area (Figure 9). Some of these features can cause water features to appear to be floating in the final DEM (Figure 10). However, viewing the LiDAR data in profile (Figure 11) shows that the water is at the same elevation as the hydraulic structure and while it may appear to be floating above the surrounding terrain, it is correctly within a structure and not actually floating above the surrounding terrain.

Figure 9: Hydraulic structure located in tile 18TYM4611

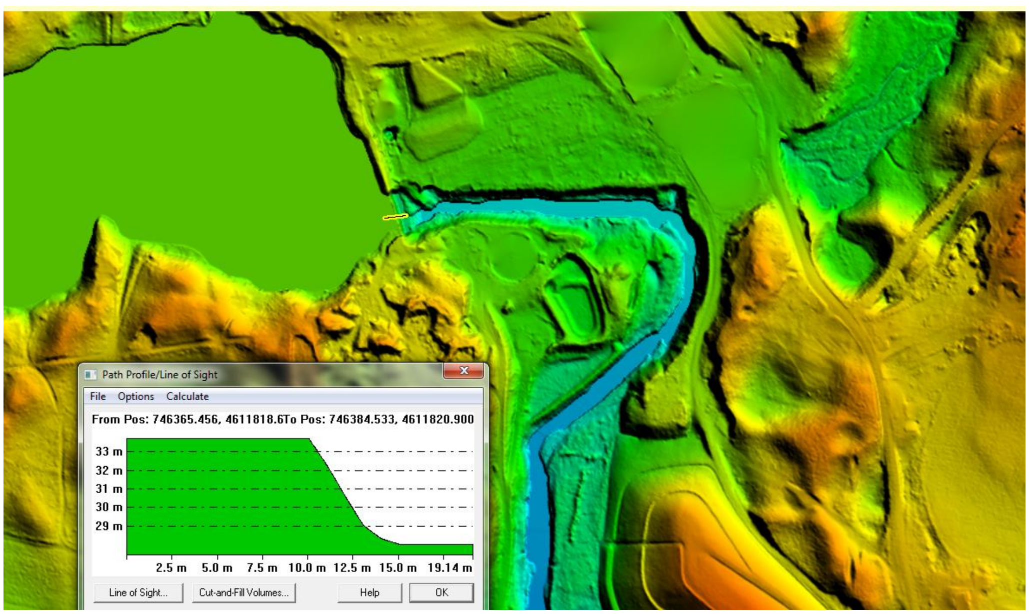


Figure 10: DEM of tile 18TYM4611. A section of water body appears to floating above the surrounding terrain and connecting hydrologic feature.

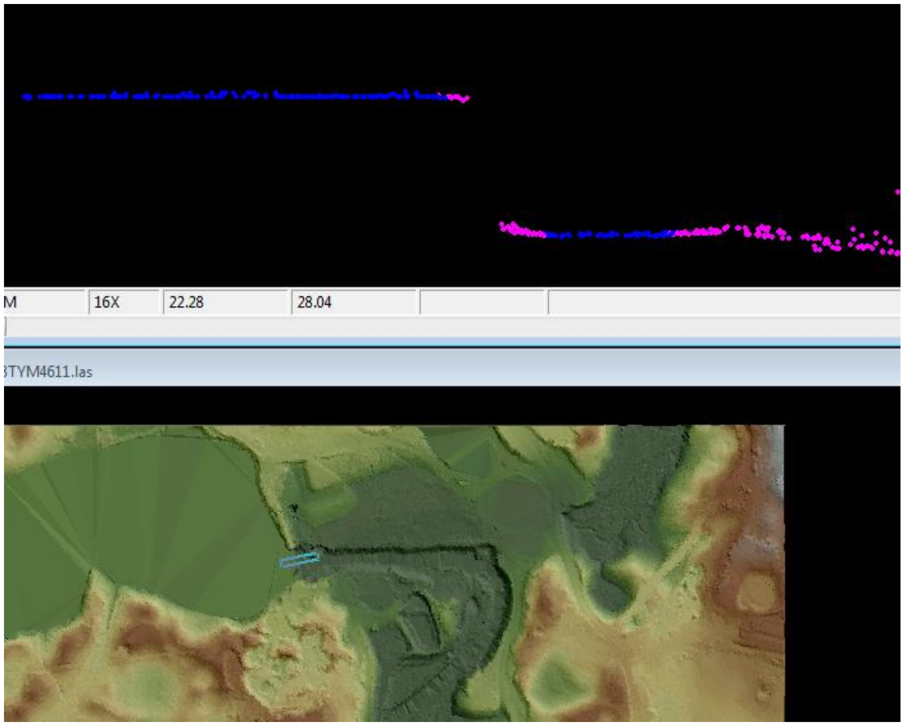


Figure 11: LiDAR data of tile 18TYM4611. The top view shows a profile of the hydraulic structure where water points are blue and ground points are pink. The bottom view shows a TIN of the area and the location of the profile. The profile shows that the hydraulic structure has correctly been left as ground to show a barrier of the water. The water only appears to be floating because it is at the same elevation of the structure but is correctly constrained by the structure and therefore not floating.

c. *Flight Line Ridges:* Dewberry reviewed DZ orthos to ensure acceptable calibration and relative accuracy of the Connecticut data. No major issues were identified. During manual review of the data, a limited number of flight line ridges were identified. These ridges, while somewhat visible in the final DEMs are within project specifications. An example is shown in the figure below.

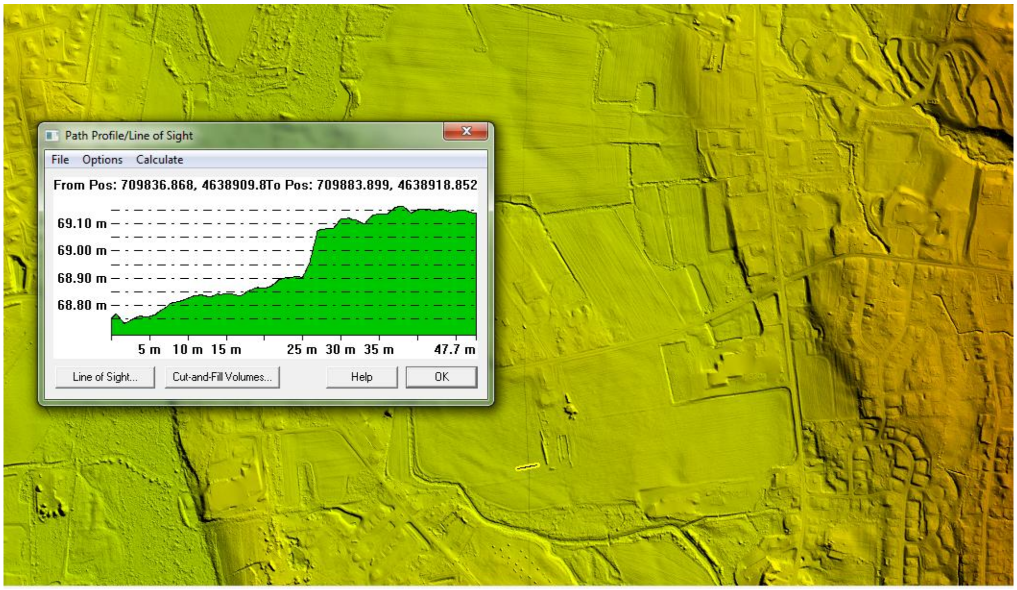


Figure 12: DEMs for tiles 18TYM0939 and 18TYM0938. The flight line ridge is less than 20 cm. Overall, the Connecticut data meets the project specifications for 10cm RMSE relative accuracy.

3.4 Conclusion

The dataset conforms to project specifications for format and header values. The spatial projection information and classification of points is correct. Buildings, vegetation and other artifacts have been removed from the bare earth ground. Water features that appear to be floating by significant amounts above surrounding features are due to hydraulic structures that are present throughout the dataset. A limited number of flight line ridges are present in the dataset, but these ridges are within project specifications.

3 Survey Vertical Accuracy Checkpoints

PT. #	NORTHING	EASTING	ELEVS.
	UTM Zone 18N		
POINT ID	**NORTHING (M)**	**EASTING (M)**	**ELEVATION (M)**
FO-1	4653267.58	710583.80	57.48
FO-2	4650474.77	725680.91	241.42
FO-3	4654265.76	737742.48	219.09
FO-4	4648614.22	757590.13	105.98
FO-5	4634319.37	758163.84	72.41
FO-6	4633196.45	746788.54	213.62
FO-7	4637837.41	734106.85	143.23
FO-8	4635710.63	701803.46	28.39
FO-9	4630782.93	719335.80	185.21
FO-10	4617047.51	703811.64	99.13
FO-11	4612436.40	723314.42	177.88

FO-12	4619654.81	734429.06	55.56
FO-13	4623199.97	757641.37	53.61
FO-14	4609018.60	752225.79	62.26
FO-15	4606871.54	739139.85	48.11
FO-16	4593928.54	727098.02	68.46
FO-17	4597256.49	713603.52	74.47
FO-18	4576720.59	728918.76	24.62
FO-19	4583351.05	737052.71	28.89
FO-20	4595389.34	754620.54	56.23
FO-21	4603740.54	763478.06	136.61
GWC-1	4643799.44	699425.78	25.75
GWC-2	4645076.29	717948.71	237.90
GWC-3	4651232.85	733720.40	281.81
GWC-4	4647726.90	752410.89	112.41
GWC-5	4638474.95	749181.87	162.07
GWC-6	4638362.57	741354.21	127.80
GWC-7	4644487.53	732675.86	242.14
GWC-8	4636611.07	713411.05	155.37
GWC-9	4625121.06	699031.72	23.15
GWC-10	4619471.38	710319.43	229.86
GWC-11	4622822.48	723806.83	86.79
GWC-12	4622180.95	743917.16	154.74
GWC-13	4612463.50	762270.63	134.59
GWC-14	4611212.56	733728.14	133.45
GWC-15	4606051.83	699950.60	35.52
GWC-16	4603187.43	712773.65	24.26
GWC-17	4600525.45	733223.07	135.65
GWC-18	4602428.66	748732.65	63.72
GWC-19	4589882.66	754004.63	16.68
GWC-20	4581299.95	749993.14	55.62
GWC-21	4580035.49	740703.63	5.20
GWC-22	4582724.00	722383.41	42.40
GWC-23	4596850.10	721561.70	85.73
OT-1	4643654.39	709202.09	66.10
OT-2	4649858.13	719006.02	161.61
OT-3	4654539.37	729194.99	279.17
OT-4	4654317.04	751150.36	134.73
OT-5	4642740.11	757797.01	73.66
OT-6	4642699.67	742250.19	151.77
OT-7	4640536.63	723271.84	139.58
OT-8	4626107.88	706699.10	79.51

OT-9	4632199.75	727335.45	166.31
OT-10	4628521.37	745512.49	116.22
OT-11	4622174.72	763746.71	89.45
OT-12	4620803.00	752274.15	65.22
OT-13	4624694.24	734890.55	88.11
OT-14	4605874.19	708291.26	127.47
OT-15	4605303.48	722061.27	106.68
OT-16	4616841.69	716819.60	137.10
OT-17	4589054.64	722720.38	20.12
OT-18	4580952.37	725414.21	12.74
OT-19	4591946.74	740889.28	38.16
OT-20	4583697.30	745267.38	52.00
OT-21	4585544.53	758801.49	28.91
OT-22	4597361.93	751717.01	39.30
OT-23	4607209.18	760988.21	76.87

Table 5: Connecticut LiDAR surveyed accuracy checkpoints

4.1 Survey Checkpoints not used in vertical accuracy testing.

Five (5) checkpoints were surveyed in non-ideal locations for testing LiDAR data. Some of these checkpoints were located on sloped terrain. Due to the horizontal spread of the sensor laser, survey checkpoints should be located on flat terrain to ensure LiDAR returns will be measuring a uniform surface and not a sloped surface which could introduce error into the vertical accuracy calculations. Additionally, some of these checkpoints were not used because they are located in land cover, such as impenetrable brush, or next to obstructions, such as trees or buildings, that do that do not give the LiDAR sensor an adequate chance to measure the ground surface.

Additional checkpoints are normally surveyed in case some of the checkpoints are deemed unusable. Even after removing these five checkpoints from the dataset, there were still 62 checkpoints remaining for the vertical accuracy testing, meeting project requirements of 60 total checkpoints comprised of 20 checkpoints in each land cover category. Table 6, below, identifies checkpoints not used in the vertical accuracy testing.

Point ID	Easting	Northing	Elevation
OT-6	742250.19	4642699.67	151.77
GWC-4	752410.89	4647726.90	112.41
FO-12	734429.06	4619654.81	55.56
GWC-14	733728.14	4611212.56	133.45
GWC-13	762270.63	4612463.50	134.59

Table 6: Checkpoints not used in vertical accuracy testing.

Below are examples of two checkpoints that were not used in vertical accuracy testing.

Figure 13: Survey Checkpoint GWC-13. This checkpoint is located on sloped terrain, better shown in the profile below.

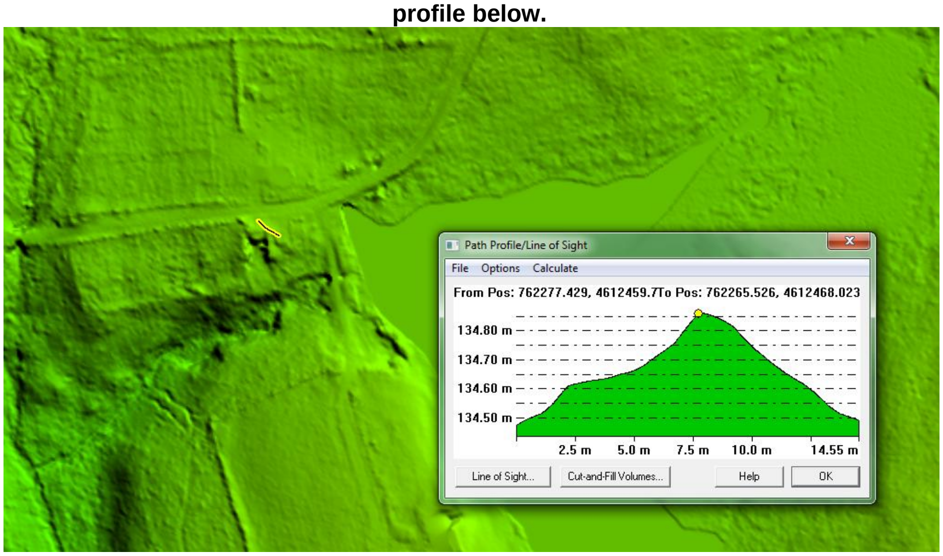


Figure 14: DEM surface and profile showing that survey checkpoint GWC-13 is poorly placed, located on a slope, and therefore was not used in vertical accuracy testing.

Figure 15: Survey Checkpoint GWC-4. This checkpoint is located in impenetrable brush that does not adequately give the LiDAR sensor a chance to measure the ground surface. Due to the poor placement of this checkpoint, it was not used during vertical accuracy testing.

5 LiDAR Vertical Accuracy Statistics & Analysis

5.1 Background

Dewberry tests and reviews project data both quantitatively (for accuracy) and qualitatively (for usability).

For quantitative assessment (i.e. vertical accuracy assessment), sixty-seven (67) check points were surveyed for the project and are located within open terrain, grass, weeds, crops, and forest land cover categories. The checkpoints were surveyed for the project using RTK survey methods. A survey report was produced which details and validates how the survey was completed for this project.

Checkpoints were evenly distributed throughout the project area so as to cover as many flight lines as possible using the “dispersed method” of placement. Only sixty-two (62) check points were used to calculate the vertical accuracy as five (5) checkpoints were collected in inappropriate locations, such as on slopes or next to objects that would obscure LiDAR returns.

5.2 Vertical Accuracy Test Procedures

FVA (Fundamental Vertical Accuracy) is determined with check points located only in land cover category (1), open terrain (grass, dirt, sand, and/or rocks), where there is a very high probability that the LiDAR sensor will have detected the bare-earth ground surface and where random errors are expected to follow a normal error distribution. The FVA determines how well the calibrated LiDAR sensor performed. With a normal error distribution, the vertical accuracy at the 95% confidence level is computed as the vertical root mean square error (RMSEz) of the checkpoints x 1.9600. For the Connecticut LiDAR project, vertical accuracy must be 18.5 cm or less based on an RMSEz of 9.25 cm x 1.9600.

CVA (Consolidated Vertical Accuracy) is determined with all checkpoints in all land cover categories combined where there is a possibility that the LiDAR sensor and post-processing may yield elevation errors that do not follow a normal error distribution. CVA at the 95% confidence level equals the 95th percentile error for all checkpoints in all land cover categories combined. The Connecticut LiDAR Project CVA standard is 18.5 cm at the 95% confidence level. The CVA is accompanied by a listing of the 5% outliers that are larger than the 95th percentile used to compute the CVA; these are always the largest outliers that may depart from a normal error distribution. Here, $Accuracy_z$ differs from CVA because $Accuracy_z$ assumes elevation errors follow a normal error distribution where RMSE procedures are valid, whereas CVA assumes LiDAR errors may not follow a normal error distribution in vegetated categories, making the RMSE process invalid.

The relevant testing criteria are summarized in Table 7.

Quantitative Criteria	Measure of Acceptability
Consolidated Vertical Accuracy (CVA) in all land cover categories combined = 95% confidence lever	18.5 cm (based on combined 95th percentile)
Fundamental Vertical Accuracy (FVA) in open terrain using RMSEz *1.9600	18.5 cm (based on RMSEz * 1.9600)

Table 7: Acceptance Criteria

5.3 Vertical Accuracy Testing Steps

The primary QA/QC vertical accuracy testing steps used by Dewberry are summarized as follows:

1. Dewberry's team surveyed QA/QC vertical checkpoints in accordance with the project's specifications. Figure 16 shows the location of the checkpoints.
2. Next, Dewberry interpolated the bare-earth LiDAR DEM to provide the z-value for each of the 62 checkpoints.
3. Dewberry then computed the associated z-value differences between the interpolated z-value from the LiDAR data and the ground truth survey checkpoints and computed CVA values.
4. The data were analyzed by Dewberry to assess the accuracy of the data. The review process examined the various accuracy parameters as defined by the scope of work. The overall descriptive statistics of each dataset were computed to assess any trends or anomalies. This report provides tables, graphs and figures to summarize and illustrate data quality.

Figure 16 shows the location of the QA/QC checkpoints within the project area.

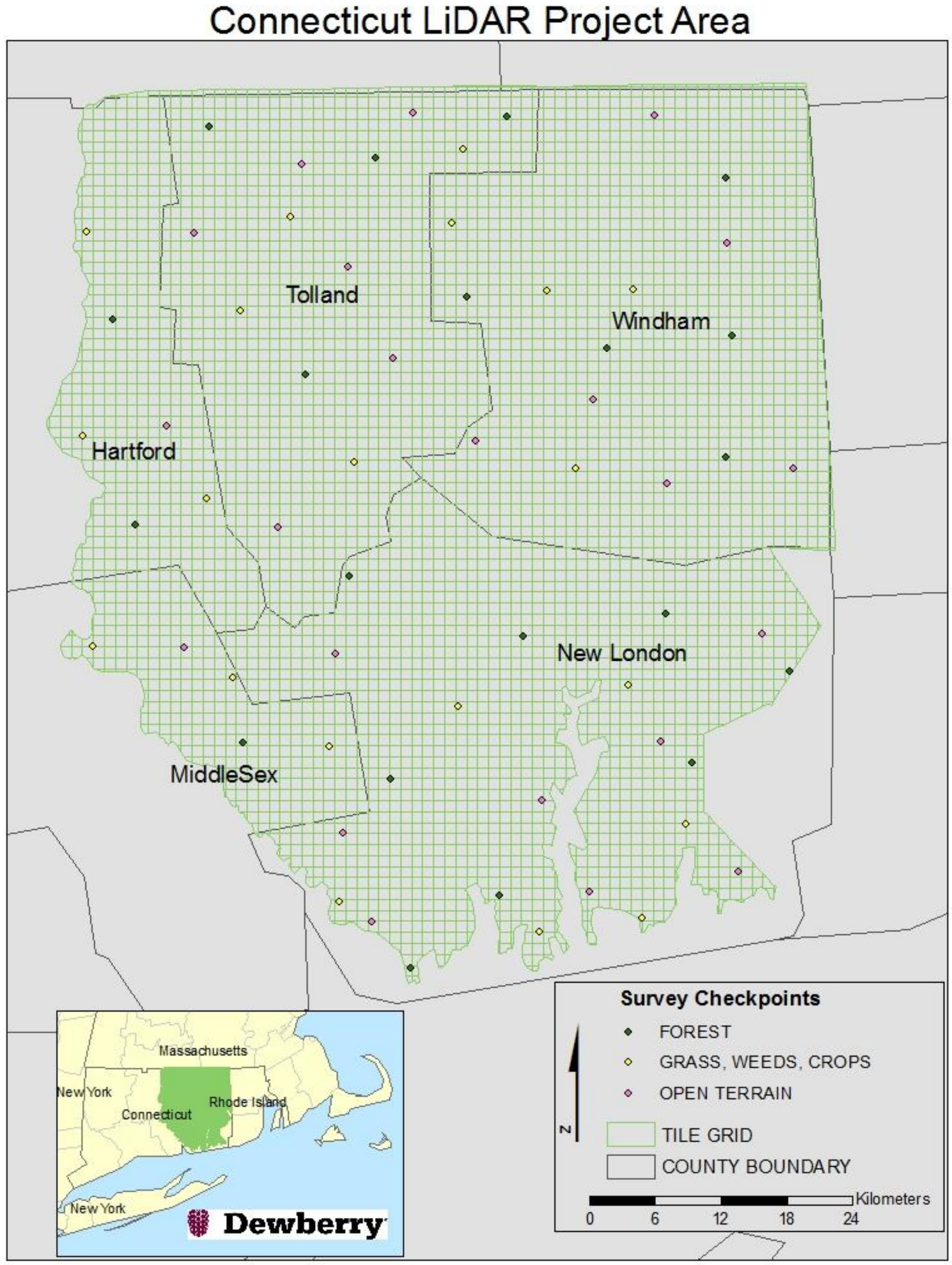


Figure 16: Location of QA/QC Checkpoints

5.4 Vertical Accuracy Results

Table 8 summarizes the tested vertical accuracy resulting from a comparison of the surveyed checkpoints to the elevation values present within the LiDAR LAS files.

Land Cover Category	# of Points	FVA — Fundamental Vertical Accuracy (RMSEz x 1.9600) Spec=0.185 m	CVA — Consolidated Vertical Accuracy (95th Percentile) Spec=0.185 m	SVA-Supplemental Vertical Accuracy (95th Percentile) Target=0.185 m
Consolidated	62		0.17	
Open Terain	22	0.09		
Grass/Weeds/Crops	20			0.17
Forest	20			0.21

Table 8: FVA and CVA Vertical Accuracy at 95% Confidence Level

The $RMSE_z$ for open terrain checkpoints tested 0.05 m, within the target criteria of 0.0925 m. Compared with the 0.185 m specification, the FVA tested 0.09 m at the 95% confidence level based on $RMSE_z$ x 1.9600.

Compared with the 0.185 m specification, CVA for all checkpoints (all land cover categories combined) tested 0.17 m at the 95% confidence level based on the 95th percentile.

Supplemental vertical accuracy (SVA) is tested for each individual land cover category that is not open terrain. The SVA of each land cover category has a target value of 0.185 m at the 95% confidence level based on the 95^{th} percentile. SVA uses target values as each land cover category tested does not have to meet the target specification as long as the consolidated vertical accuracy passes. Grass, weeds, and crops tested 0.17 m and forest tested 0.21 m compared to the 0.185 m target specification.

Figure 16 illustrates the magnitude of the differences between the QA/QC checkpoints and LiDAR data. This shows that the majority of LiDAR elevations were within +/- 0.10 m of the checkpoints elevations, but there were some outliers where LiDAR and checkpoint elevations differed by up to + 0.24 m.

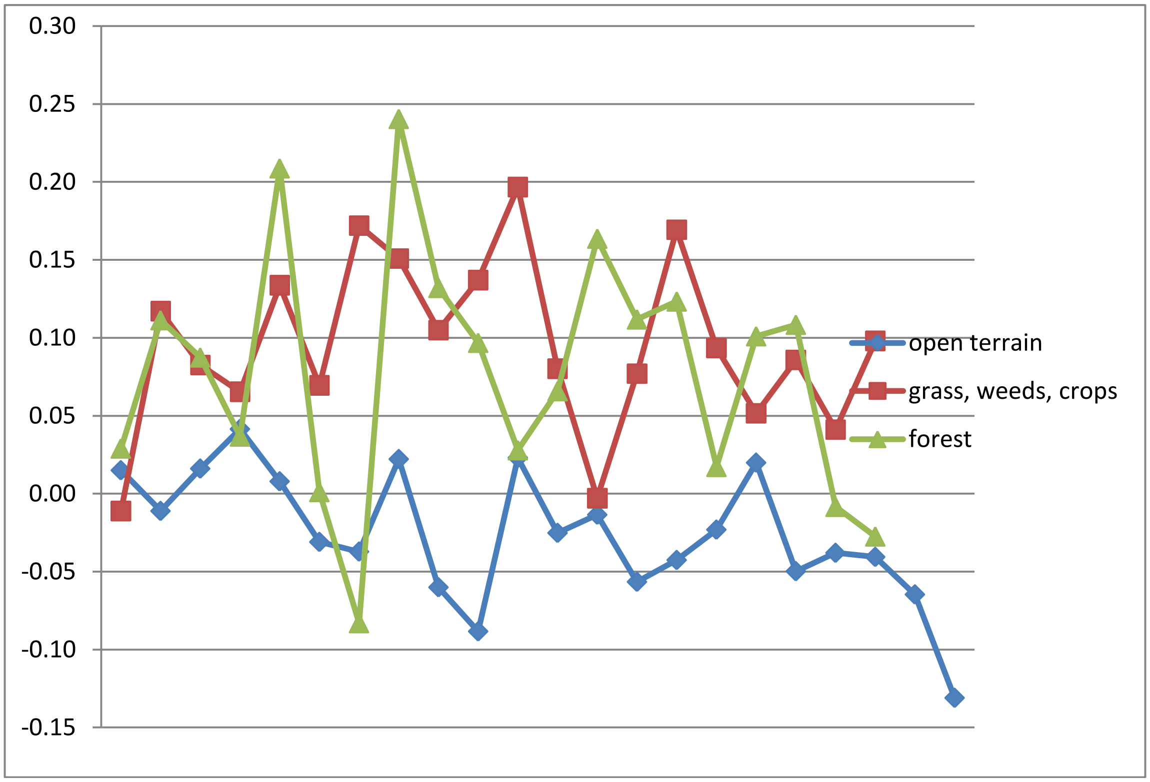


Figure 16: Magnitude of Elevation Discrepancies

Table 9 lists the 5% outliers that are larger than the 95th percentile, or 0.17 meters.

pointNo	NAD 1983 UTM Zone 18N		NAVD88	LiDAR Z (m)	Delta Z
	Easting - X (m)	Northing - Y (m)	Survey Z (m)		
GWC-2	717948.71	4645076.29	237.90	238.10	0.20
FO-5	758163.84	4634319.37	72.41	72.61	0.21
FO-21	763478.06	4603740.54	136.61	136.85	0.24

Table 9: 5% Outliers

Table 10 provides overall descriptive statistics.

100 % of Totals	RMSE (m) Open Terrain Spec=0.0925 m	Mean (m)	Median (m)	Skew	Std Dev (m)	# of Points	Min (m)	Max (m)
Consolidated		0.07	0.04	0.19	0.08	62	-0.13	0.24
Open Terrain	0.05	0.04	-0.03	-0.55	0.04	22	-0.13	0.04
Grass/Weeds/Crops		0.10	0.09	-0.10	0.05	20	-0.01	0.20
Forest		0.09	0.09	0.10	0.08	20	-0.08	0.24

Table 10: Overall Descriptive Statistics

Figure 17 illustrates a histogram of the associated elevation discrepancies between the QA/QC checkpoints and elevations interpolated from the LiDAR triangulated irregular network (TIN). The frequency shows the number of discrepancies within each band of elevation differences. The discrepancies vary between a low of -0.15 m and a high of +0.24 m. The histogram shows that the majority of the discrepancies cluster around zero, but the dataset is skewed with slightly more errors on the positive side. The vast majority of points are within the ranges -0.05 m to +0.10 m.

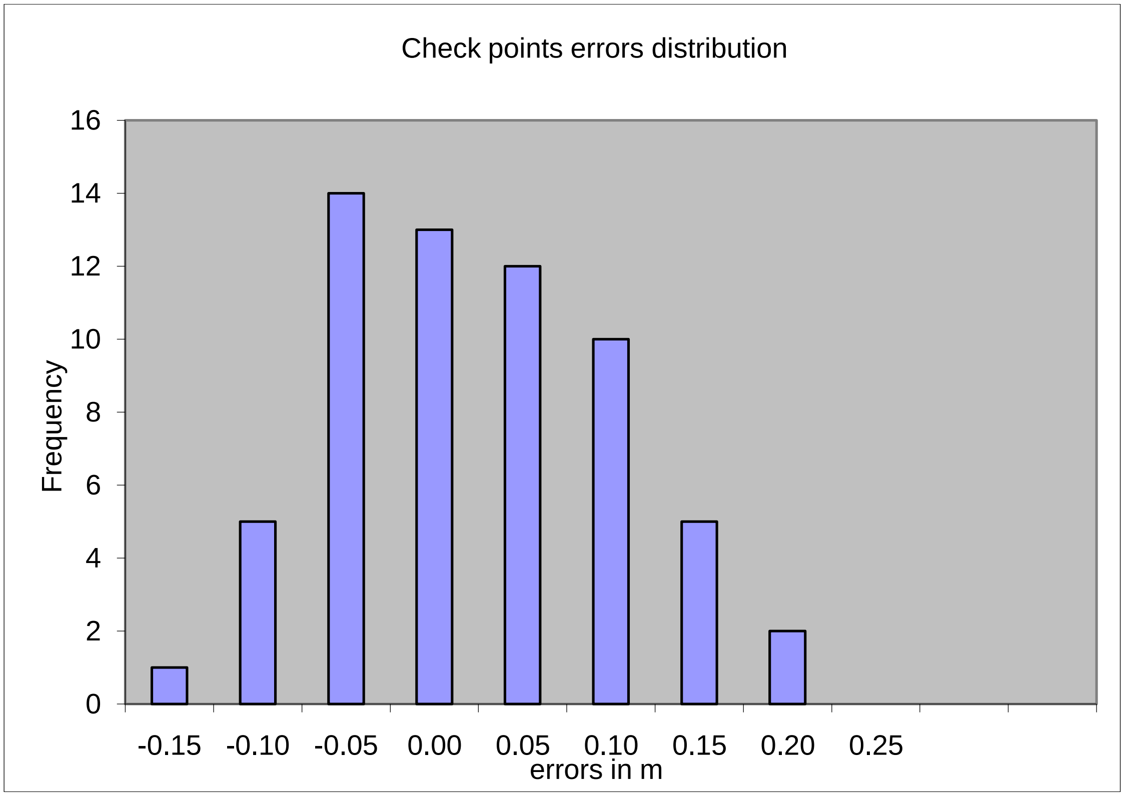


Figure 17: Histogram of Elevation Discrepancies within errors in meters

5.5 Conclusion

Based on the vertical accuracy testing conducted by Dewberry, the LiDAR dataset for the Connecticut LiDAR Project satisfies the project's pre-defined vertical accuracy criteria.

6 Breakline Production & Qualitative Assessment Report

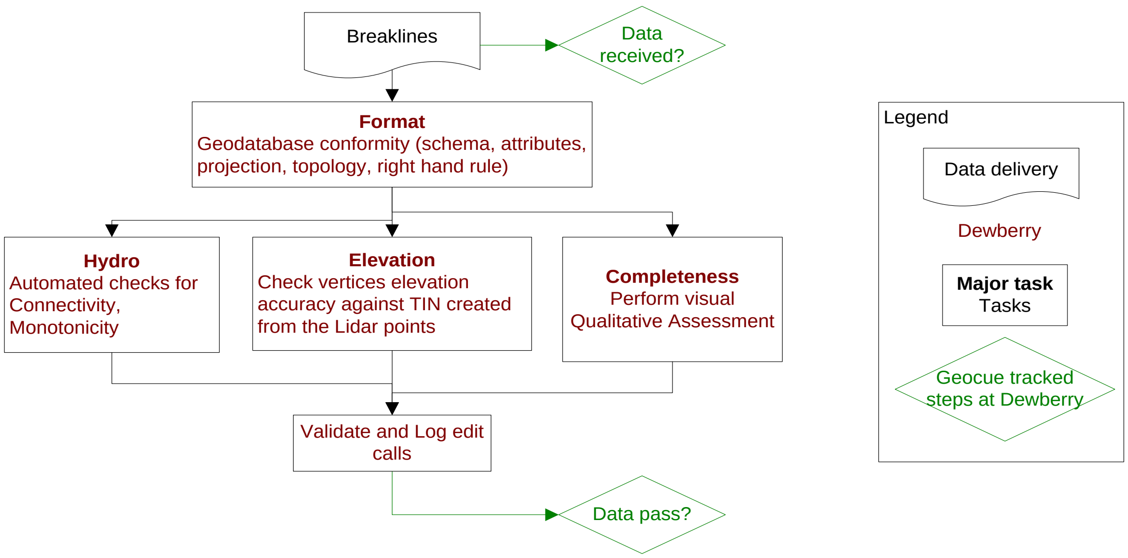
6.1 Breakline Production Methodology

Dewberry used GeoCue software to develop LiDAR stereo models of the Connecticut LiDAR Project area so the LiDAR derived data could be viewed in 3-D stereo using Socet Set softcopy photogrammetric software. Using LiDARgrammetry procedures with LiDAR intensity imagery, Dewberry stereo-compiled the two types of hard breaklines in accordance with the project's Data Dictionary.

All drainage breaklines are monotonically enforced to show downhill flow. Water bodies are reviewed in stereo and the lowest elevation is applied to the entire waterbody.

6.2 *Breakline Qualitative Assessment*

Dewberry completed breakline qualitative assessments according to a defined workflow. The following workflow diagram represents the steps taken by Dewberry to provide a thorough qualitative assessment of the breakline data.



6.3 *Breakline Topology Rules*

Automated checks are applied to hydro features to validate the 3D connectivity of the feature and the monotonicity of the hydrographic breaklines. Dewberry's major concern was that the hydrographic breaklines have a continuous flow downhill and that breaklines do not undulate. Error points are generated at each vertex not complying with the tested rules and these potential edit calls are then visually validated during the visual evaluation of the data. This step also helped validate that breakline vertices did not have excessive minimum or maximum elevations and that elevations are consistent with adjacent vertex elevations.

The next step is to compare the elevation of the breakline vertices against the elevation extracted from the ESRI Terrain built from the LiDAR ground points, keeping in mind that a discrepancy is expected because of the hydro-enforcement applied to the breaklines and because of the interpolated imagery used to acquire the breaklines. A given tolerance is used to validate if the elevations do not differ too much from the LiDAR.

Dewberry's final check for the breaklines was to perform a full qualitative analysis. Dewberry compared the breaklines against LiDAR intensity images to ensure breaklines were captured in the required locations. The quality control steps taken by Dewberry are outlined in the QA Checklist below.

6.4 *Breakline QA/QC Checklist*

Project Number/Description: TO 0002 Connecticut LiDAR

Overview

☒ All Feature Classes are present in GDB

☒ All features have been loaded into the geodatabase correctly. Ensure feature classes with subtypes are domained correctly.

☒ The breakline topology inside of the geodatabase has been validated. See Data Dictionary for specific rules

☒ Projection/coordinate system of GDB is accurate with project specifications

Perform Completeness check on breaklines using either intensity or ortho imagery

☒ Check entire dataset for missing features that were not captured, but should be to meet baseline specifications or for consistency (See Data Dictionary for specific collection rules). NHD data will be used to help evaluate completeness of collected hydrographic features. Features should be collected consistently across tile bounds within a dataset as well as be collected consistently between datasets.

☒ Check to make sure breaklines are compiled to correct tile grid boundary and there is full coverage without overlap

☒ Check to make sure breaklines are correctly edge-matched to adjoining datasets if applicable. Ensure breaklines from one dataset join breaklines from another dataset that are coded the same and all connecting vertices between the two datasets match in X,Y, and Z (elevation). There should be no breaklines abruptly ending at dataset boundaries and no discrepancies of Z-elevation in overlapping vertices between datasets.

Compare Breakline Z elevations to LiDAR elevations

☒ Using a terrain created from LiDAR ground points and water points and GeoFIRM tools, drape breaklines on terrain to compare Z values. Breakline elevations should be at or below the elevations of the immediately surrounding terrain. This should be performed before other breakline checks are completed.

Perform automated data checks using PLTS

The following data checks are performed utilizing ESRI's PLTS extension. These checks allow automated validation of 100% of the data. Error records can either be written to a table for future correction, or browsed for immediate correction. PLTS checks should always be performed on the full dataset.

☒ Perform "adjacent vertex elevation change check" on the Inland Ponds feature class (Elevation Difference Tolerance=.001 m). This check will return Waterbodies whose vertices are not all identical. This tool is found under "Z Value Checks."

☒ Perform "unnecessary polygon boundaries check" on Inland Ponds, and Inland Streams feature classes. This tool is found under "Topology Checks."

☒ Perform "duplicate geometry check" on (inland streams to inland streams), (inland ponds to inland ponds), (inland ponds to inland streams). Attributes do not need to be checked during this tool. This tool is found under "Duplicate Geometry Checks."

☒ Perform "geometry on geometry check" on (inland ponds to inland streams). Spatial relationship is contains, attributes do not need to be checked. This tool is found under "Feature on Feature Checks."

☒ Perform "polygon overlap/gap is sliver check" on (inland streams to inland streams), (inland ponds to inland ponds), and (inland ponds to inland streams). Maximum Polygon Area is not required. This tool is found under "Feature on Feature Checks."

Perform Dewberry Proprietary Tool Checks

☒ Perform monotonicity check on inland streams features using "A3_checkMonotonicityStreamLines." This tool looks at line direction as well as elevation. Features in the output shapefile attributed with a "d" are correct monotonically, but were compiled from low elevation to high elevation. These errors can be ignored. Features in the output shapefile attributed with an "m" are not correct monotonically and need elevations to be corrected. Input features for this tool need to be in a geodatabase. Z tolerance is .01 m. Polygons need to be exported as lines for the monotonicity tool.

☒ Perform connectivity check between (inland ponds to inland streams) using the tool "07_CheckConnectivityForHydro." The input for this tool needs to be in a geodatabase. The output is a shapefile showing the location of overlapping vertices from the polygon features and polyline features that are at different Z-elevation. The unnecessary polygon boundary check must be run and all errors fixed prior to performing connectivity check. If there are exceptions to the polygon boundary rule then that feature class must be checked against itself, i.e. inland streams to inland streams.

Metadata

☒ Each XML file (1 per feature class) is error free as determined by the USGS MP tool

☒ Metadata content contains sufficient detail and all pertinent information regarding source materials, projections, datums, processing steps, etc. Content should be consistent across all feature classes.

Completion Comments: Complete – Approved

6.5 Data Dictionary

Dewberry®

LiDARgrammetry Data Dictionary & Stereo Compilation Rules

For the Connecticut LiDAR Project

September 27, 2010

6.5.1 *Horizontal and Vertical Datum*

The horizontal datum shall be North American Datum of 1983, Units in meters. The vertical datum shall be referenced to the North American Vertical Datum of 1988 (NAVD 88), Units in meters. Geoid09 shall be used to convert ellipsoidal heights to orthometric heights.

6.5.2 *Coordinate System and Projection*

All data shall be projected to UTM Zone 18N, Horizontal Units in meters and Vertical Units in meters.

6.5.3 *Inland Streams and Rivers*

Feature Dataset: BREAKLINES
Feature Class: STREAMS_AND_RIVERS
Feature Type: Polygon
Contains M Values: No
Contains Z Values: Yes
Annotation Subclass: None
XY Resolution: Accept Default Setting
Z Resolution: Accept Default Setting

XY Tolerance: 0.003
Z Tolerance: 0.001

Description
This polygon feature class will depict linear hydrographic features with a width greater than 50 feet.

Table Definition

Field Name	Data Type	Allow Null Values	Default Value	Domain	Precision	Scale	Length	Responsibility
OBJECTID	Object ID							Assigned by Software
SHAPE	Geometry							Assigned by Software
SHAPE_LENGTH	Double	Yes			0	0		Calculated by Software
SHAPE_AREA	Double	Yes			0	0		Calculated by Software

Feature Definition

Description	Definition	Capture Rules
Streams and Rivers	Linear hydrographic features such as streams, rivers, canals, etc. with an average width greater than 50 feet in length. In the case of embankments, if the feature forms a natural dual line channel, then capture it consistent with the capture rules. Other natural or manmade embankments will	Capture features showing dual line (one on each side of the feature). Average width shall be greater than 50 feet to show as a double line. Each vertex placed should maintain vertical integrity and data is required to show "closed polygon". Generally both banks shall be collected to show consistent downhill flow. There are exceptions to this rule where a small branch or offshoot of the stream or river is present. The banks of the stream must be captured at the same elevation to ensure flatness of the water feature. If the elevation of the

	not qualify for this project.	banks appears to be different see the task manager or PM for further guidance. Breaklines must be captured at or just below the elevations of the immediately surrounding terrain. Under no circumstances should a feature be elevated above the surrounding LiDAR points. Acceptable variance in the negative direction will be defined for each project individually. These instructions are only for docks or piers that follow the coastline or water's edge, not for docks or piers that extend perpendicular from the land into the water. If it can be reasonably determined where the edge of water most probably falls, beneath the dock or pier, then the edge of water will be collected at the elevation of the water where it can be directly measured. If there is a clearly-indicated headwall or bulkhead adjacent to the dock or pier and it is evident that the waterline is most probably adjacent to the headwall or bulkhead, then the water line will follow the headwall or bulkhead at the elevation of the water where it can be directly measured. If there is no clear indication of the location of the water's edge beneath the dock or pier, then the edge of water will follow the outer edge of the dock or pier as it is adjacent to the water, at the measured elevation of the water. Every effort should be made to avoid breaking a stream or river into segments. Dual line features shall break at road crossings (culverts). In areas where a bridge is present the dual line feature shall continue through the bridge. Islands: The double line stream shall be captured around an island if the features on either side of the island meet the criteria for capture. In this case a segmented polygon shall be used around the island in order to allow for the island feature to remain as a "hole" in the feature.

6.5.4 Inland Ponds and Lakes

Feature Dataset: BREAKLINES
Feature Class: PONDS_AND_LAKES
Feature Type: Polygon
Contains M Values: No
Contains Z Values: Yes
Annotation Subclass: None
XY Resolution: Accept Default Setting
Z Resolution: Accept Default Setting

XY Tolerance: 0.003
Z Tolerance: 0.001

Description

This polygon feature class will depict closed water body features that are at a constant elevation.

Table Definition

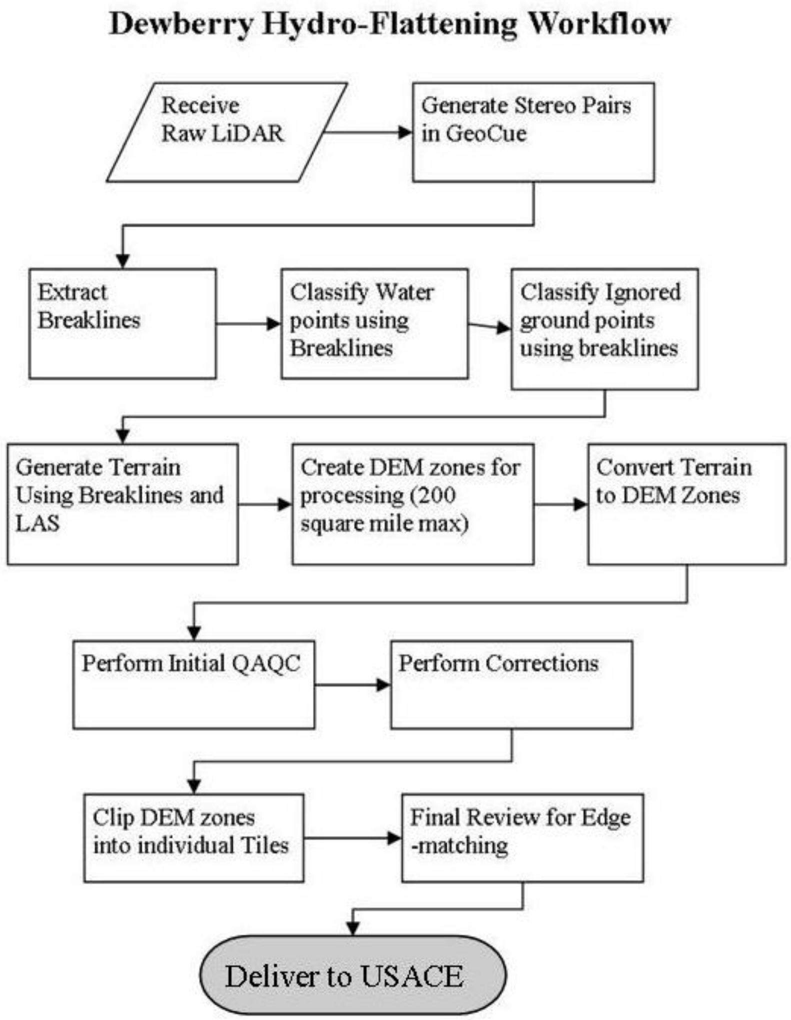
Field Name	Data Type	Allow Null Values	Default Value	Domain	Precision	Scale	Length	Responsibility
OBJECTID	Object ID							Assigned by Software
SHAPE	Geometry							Assigned by Software
SHAPE_LENGTH	Double	Yes			0	0		Calculated by Software
SHAPE_AREA	Double	Yes			0	0		Calculated by Software

Feature Definition

Description	Definition	Capture Rules
Ponds and Lakes	Land/Water boundaries of constant elevation water bodies such as lakes, reservoirs, ponds, etc. Features shall be defined as closed polygons and contain an elevation value that reflects the best estimate of the water elevation at the time of data capture. Water body features will be captured for features 2 acres in size or greater. "Donuts" will exist where there are islands within a closed water body feature greater than ½ acre in size.	Water bodies shall be captured as closed polygons with the water feature to the right. The compiler shall take care to ensure that the z-value remains consistent for all vertices placed on the water body. Breaklines must be captured at or just below the elevations of the immediately surrounding terrain. Under no circumstances should a feature be elevated above the surrounding LiDAR points. Acceptable variance in the negative direction will be defined for each project individually. An Island within a Closed Water Body Feature will also have a "donut polygon" compiled. These instructions are only for docks or piers that follow the coastline or water's edge, not for docks or piers that extend perpendicular from the land into the water. If it can be reasonably determined where the edge of water most probably falls, beneath the dock or pier, then the edge of water will be collected at the elevation of the water where it can be directly measured. If there is a clearly-indicated headwall or bulkhead adjacent to the dock or pier and it is evident that the waterline is most probably adjacent to the headwall or bulkhead, then the water line will follow the headwall or bulkhead at the elevation of the water where it can be directly measured. If there is no clear indication of the location of the water's edge beneath the dock or pier, then the edge of water will follow the outer edge of the dock or pier as it is adjacent to the water, at the measured elevation of the water.

7 DEM Production & Qualitative Assessment

7.1



DEM Production Methodology

Dewberry's utilizes ESRI software and Global Mapper for the DEM production and QC process. ArcGIS software is used to generate the products and the QC is performed in both ArcGIS and Global Mapper.

1. Generate LiDAR Stereo Pairs using GeoCue: Create stereo pairs with the raster pixel size being equal to the nominal point spacing. Stereo pairs will be created for Bare-Earth and Full-Point Cloud.
2. Extract Breaklines: Breaklines will be extracted according to the data dictionary outlined on the previous pages.
3. Classify Water Points: LAS point falling within hydrographic breaklines shall be classified to ASPRS class 9 using TerraScan. Breaklines must be prepared correctly prior to performing this task.

4. Classify Ignored Ground Points: Points within a specified distance of breaklines can be removed from the ground classification and re-classified to a separate class, usually class 10. Ignored ground points were not created for the Connecticut LiDAR project.
5. Terrain Processing: A Terrain will be generated using the Breaklines and LAS data that has been imported into Arc as a Multipoint File. If the final DEMs are to be clipped to a project boundary that boundary will be used during the generation of the Terrain.
6. Create DEM Zones for Processing: Create DEM Zones that are buffered by 2 tiles around the edges. Zones should be created in a logical manner to minimize the number of zones without creating zones to large for processing. Dewberry will make zones no larger than 200 square miles (taking into account that a DEM will fill in the entire extent not just where LiDAR is present). Once the first zone is created it must be verified against the tile grid to ensure that the cells line up perfectly with the tile grid edge.
7. Convert Terrain to Raster: Convert Terrain to raster using the DEM Zones created in step 6. In the environmental properties set the extents of the raster to the buffered Zone. For each subsequent zone, the first DEM will be utilized as the snap raster to ensure that zones consistently snap to one another.
8. Perform Initial QAQC on Zones: During the initial QA process anomalies will be identified and corrective polygons will be created.
9. Correct Issues on Zones: Corrections on zones will be performed following Dewberry's in-house correction process.
10. Extract Individual Tiles: Individual Tiles will be extracted from the zones utilizing a Dewberry proprietary tool.
11. Final QA: Final QA will be performed on the dataset to ensure that tile boundaries are seamless.

7.2 DEM Qualitative Assessment

Dewberry performed a comprehensive qualitative assessment of the 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. This process was performed in ArcGIS software with the use of a tool set Dewberry has developed to verify that the raster extents match those of the tile grid and contain the correct projection information. The DEM data was reviewed at a scale of 1:8000 to review for artifacts caused by the DEM generation process and to review the hydro-flattened features. Dewberry uses Global Mapper to perform this review. Corrections are applied in Arc Map. Dewberry creates HillShade models and overlays a partially transparent colorized elevation model in order to perform the corrections. The last step is to load the DEM data into Global Mapper to ensure that the corrections are acceptable, all files are readable, and that no artifacts exist between tiles. The figure below, illustrates the detail of the final DEMs and how the DEMs display elevation changes within hydrographic features.

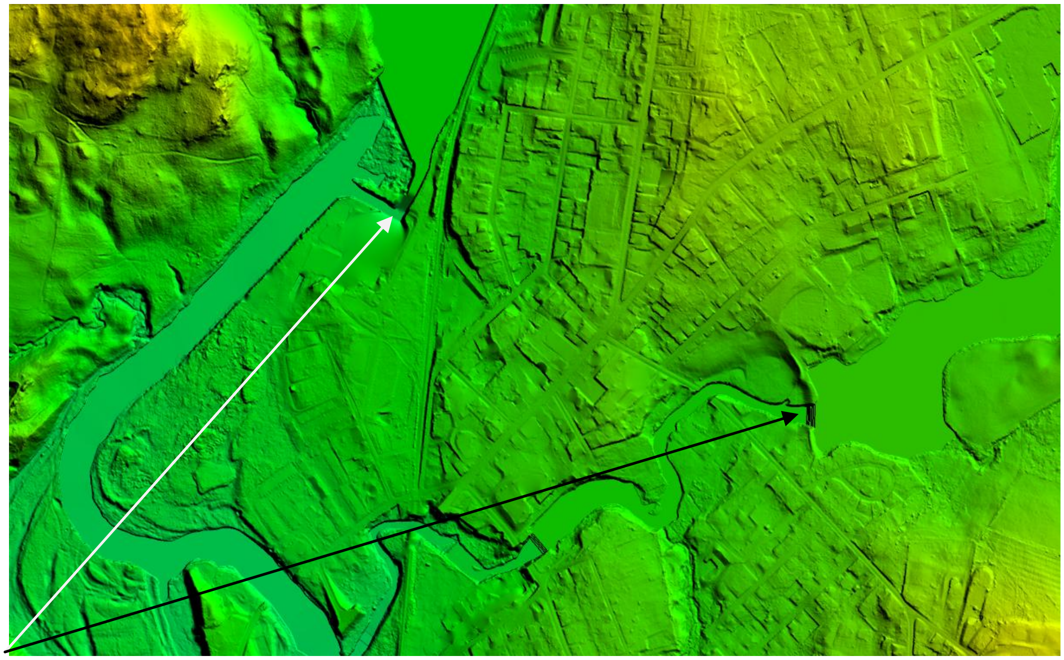


Figure 18: DEM for tile 18TBG5110

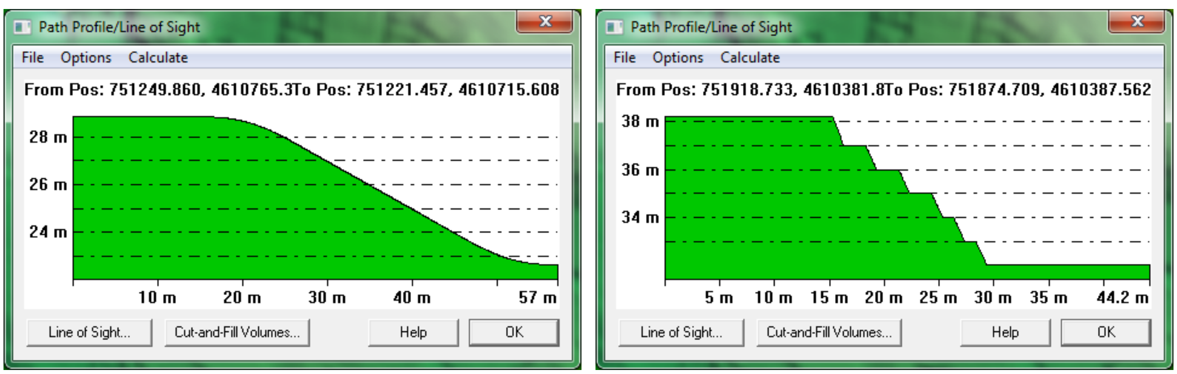


Figure 19: Profiles showing elevation changes on hydrographic features. Some elevation changes will be shown as smooth or constant slopes (left profile and white arrow). The square pixels in a raster DEM sometimes have trouble showing constant or continuous slopes. In these areas, stair steps are used to enforce monotonic breakline elevations and flatten the hydrographic feature from bank to bank (right profile and black arrow).

7.3 DEM QA/QC Checklist

Project Number/Description: TO 00002 Connecticut LiDAR

Overview

☒ Correct number of files is delivered and all files are in ESRI GRID format

☒ Verify Raster Extents

☒ Verify Projection/Coordinate System

Review

☒ Manually review bare-earth DEMs with a hillshade to check for issues with hydro-flattening process or any general anomalies that may be present. Specifically, water should be flowing downhill, water features should NOT be floating above surrounding terrain and bridges should NOT be present in bare-earth DEM. Hydrologic breaklines should be overlaid during review of DEMs.

☒ DEM cell size is 1 meter

☒ Perform final overview in Global Mapper to ensure seamless product.

Metadata

☒ Project level DEM metadata XML file is error free as determined by the USGS MP tool

☒ Metadata content contains sufficient detail and all pertinent information regarding source materials, projections, datums, processing steps, etc.

Completion Comments: Complete - Approved