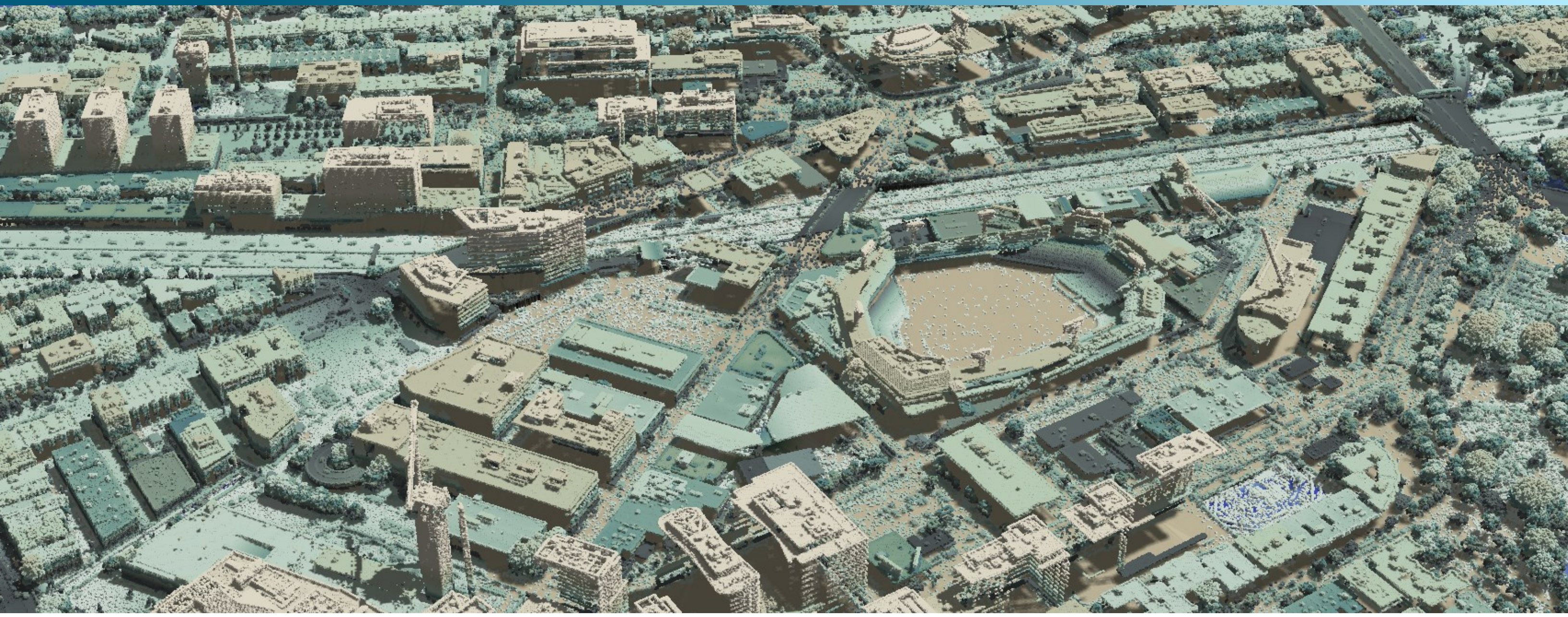
January 26, 2022



USGS 3DEP Central Eastern Massachusetts Lidar Technical Data Report

Task Order: 140G0221F0090
Project ID: 218602

Contract: G16PC00016
Work Unit ID: 218599
Work Unit ID: 226060

Prepared For:

United States Geological Survey
1400 Independence Road
Rolla, MO 65401

Prepared By:

NV5 Geospatial Corvallis
1100 NE Circle Blvd, Ste. 126
Corvallis, OR 97330
PH: 541-752-1204

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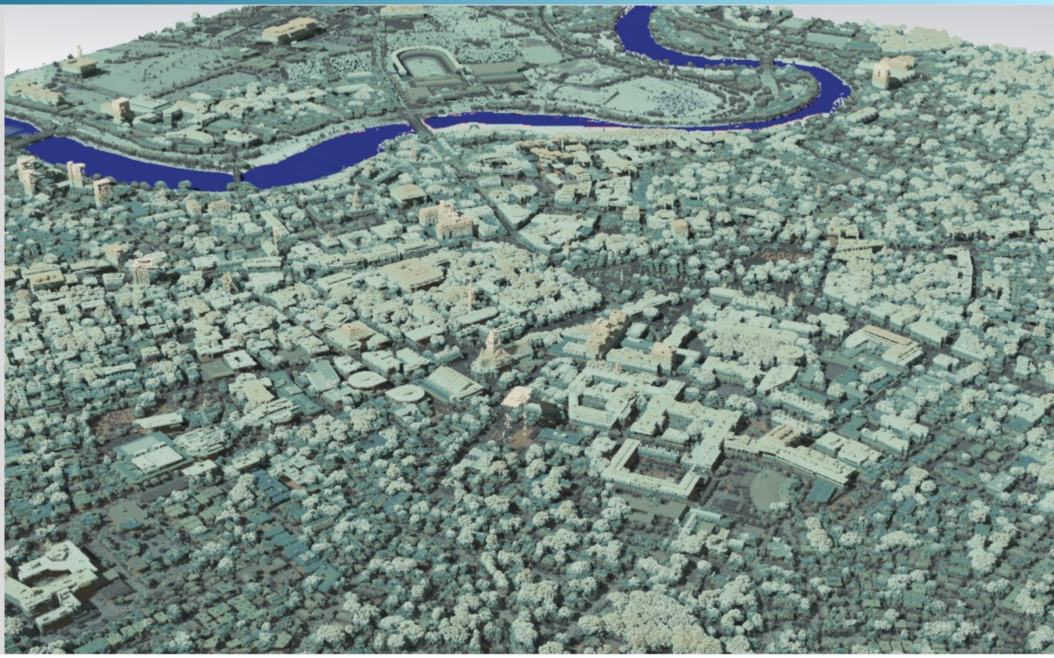
Cover Photo: A view looking north over Fenway Park in downtown Boston. The image was created from the lidar bare earth model colored by elevation overlaid with the above ground point cloud.

INTRODUCTION

This image shows a view looking south over Harvard University. The image was created from the lidar bare earth model colored by elevation overlaid with the above ground point cloud.



In March 2021, NV5 Geospatial (NV5) was contracted by USGS to collect Light Detection and Ranging (lidar) data in the spring of 2021 for 5,246 square miles of Central Eastern Massachusetts. Data were collected to aid USGS in assessing the topographic and geophysical properties of the study area and to support the USGS 3DEP initiative.

This report accompanies the delivered lidar data, and documents contract specifications, data acquisition procedures, processing methods, and analysis of the final dataset including lidar accuracy and density. Acquisition dates and acreage are shown in Table 1, a complete list of contracted deliverables provided to USGS is shown in Table 2, and the project extent is shown in Figure 1.

Table 1: Acquisition dates, acreage, and data types collected on the Central Eastern Massachusetts project area

Project Site	Contracted Acres	Contracted Square Miles	Acquisition Dates	Data Type
Central Eastern Massachusetts	3,357,050	5,246	3/20/21 – 3/23/21, 03/27/21, 04/03/21 - 04/04/21, 04/06/21, 04/08/21, 4/09/21 , 4/13/21 – 4/15/21, 4/19/21 – 4/21/21, 4/23/21, 4/24/21	Topographic Lidar

Deliverable Products

Table 2: Products delivered to USGS for the Central Eastern Massachusetts area

<table>
<tr><th colspan="2">Central Eastern Massachusetts Lidar Products
Projection: UTM Zone 19 North
Horizontal Datum: NAD83 (2011)
Vertical Datum: NAVD88 (GEOID18)
Units: Meters</th></tr>
<tr><td>Points</td><td>LAS v 1.4
• All Classified Returns</td></tr>
<tr><td>Rasters</td><td>1.5 Foot Cloud Optimized GeoTiffs
• Hydroflattened Bare Earth Models (DEM)
• Maximum Surface Height Models (DSM)
• Intensity Images
• Swath Separation Images</td></tr>
<tr><td>Vectors</td><td>Shapefiles (*.shp)
• Defined Project Area
• Master Tile Index
ESRI Geodatabase (*.gdb)
• 3D Hydroflattened Breaklines
• 3D Bridge Breaklines
• Flightline Swath Coverage Extents
• Flightline Index
ESRI Geopackage (*.gpkg)
• Ground Survey Shapes</td></tr>
</table>

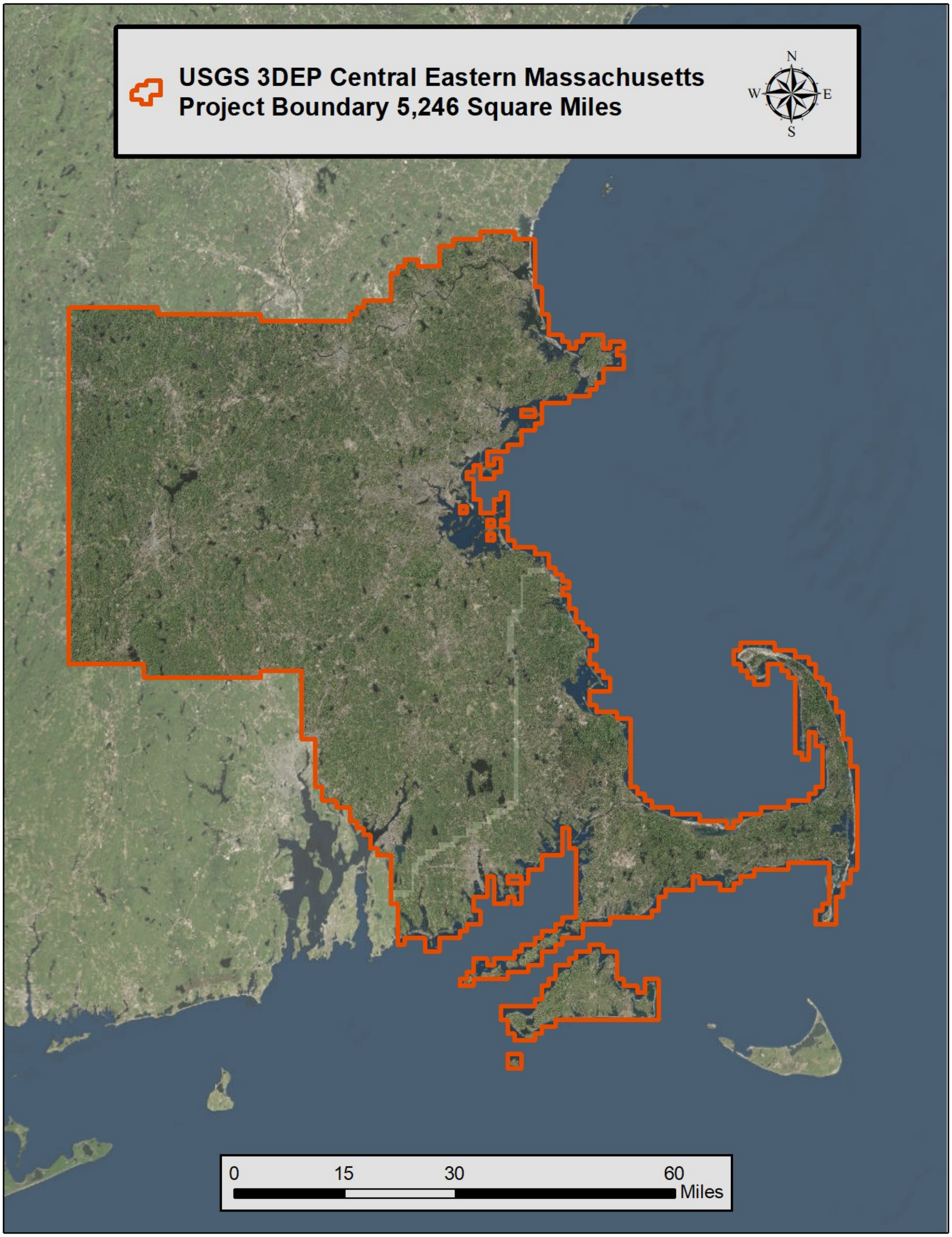


Figure 1: Location map of the Central Eastern Massachusetts project area

ACQUISITION

NV5 Geospatial’s Cessna Caravan

Planning

In preparation for data collection, NV5 Geospatial reviewed the project area and developed a specialized flight plan to ensure complete coverage of the Central Eastern Massachusetts lidar study area at the target point density of ≥8.0 points (Figure 2, Table 4). Acquisition parameters including orientation relative to terrain, flight altitude, pulse rate, scan angle, and ground speed were adapted to optimize flight paths and flight times while meeting all contract specifications.

Factors such as satellite constellation availability and weather windows must be considered during the planning stage. Any weather hazards or conditions affecting the flight were continuously monitored due to their potential impact on the daily success of airborne and ground operations. In addition, logistical considerations including private property access and potential air space restrictions were reviewed. Special care was taken to plan acquisition of tidal areas in a manner to keep tidal water fluctuations minimal resulting in fewer temporal differences in the dataset.

Additionally NV5 Geospatial contracted SurvTech Solutions, Inc. to conduct portions of the aerial survey.

Airborne Lidar Survey

The lidar survey was accomplished using Riegl VQ-1560i and Optech-T2000 lidar sensors. Table 4 summarizes the settings used to yield an average pulse density of ≥8 pulses/m^2 over the Central Eastern Massachusetts project area. The Optech-T2000 can record up to 8 range measurements per pulse while the Riegl VQ-1560i laser system can record unlimited range measurements (returns) per pulse, however a maximum of 15 returns can be stored due to LAS v1.4 file limitations. It is not uncommon for some types of surfaces (e.g., dense vegetation or water) to return fewer pulses to the lidar sensor than the laser originally emitted. The discrepancy between first return and overall delivered density will vary depending on terrain, land cover, and the prevalence of water bodies. All discernible laser returns were processed for the output dataset.

Table 3: Flight Date Table

Date	Flight Line #	Start Time (Adjusted GPS)	End Time (Adjusted GPS)
03/20/2021	100 – 115	300283276.664	300309597.998
03/21/2021	116 – 155	300371659.005	30099570.997
03/22/2021	156 – 178	300457129.005	300469808.833
03/23/2021	179 – 189	300551988.475	300555239.741
03/27/2021	500 – 529	300893612.154	300908588.611
04/03/2021	190 – 229	301489868.716	301520986.796
04/04/2021	230 – 257	301580001.589	301599165.886
04/06/2021	258 – 278	301753402.033	301774810.632

04/08/2021	5000 – 5014	301944703.292	301954686.540
04/09/2021	279 – 314, 9004	302013696.778	302043014.846
04/13/2021	5035 – 5044	302383806.929	302389470.694
04/14/2021	5045 -5057	302473805.009	302479689.217
04/15/2021	5058 – 5062	302480259.957	302483179.732
04/19/2021	315 – 323	302902713.477	302908321.959
04/20/2021	5093 -5107	302949876.960	302964089.163
04/21/2021	5063 – 5068	303034499.079	303040448.456
04/23/2021	5069 – 5078	303208301.907	303220727.244
04/24/2021	5079 – 5092	303296065.397	30336165.109

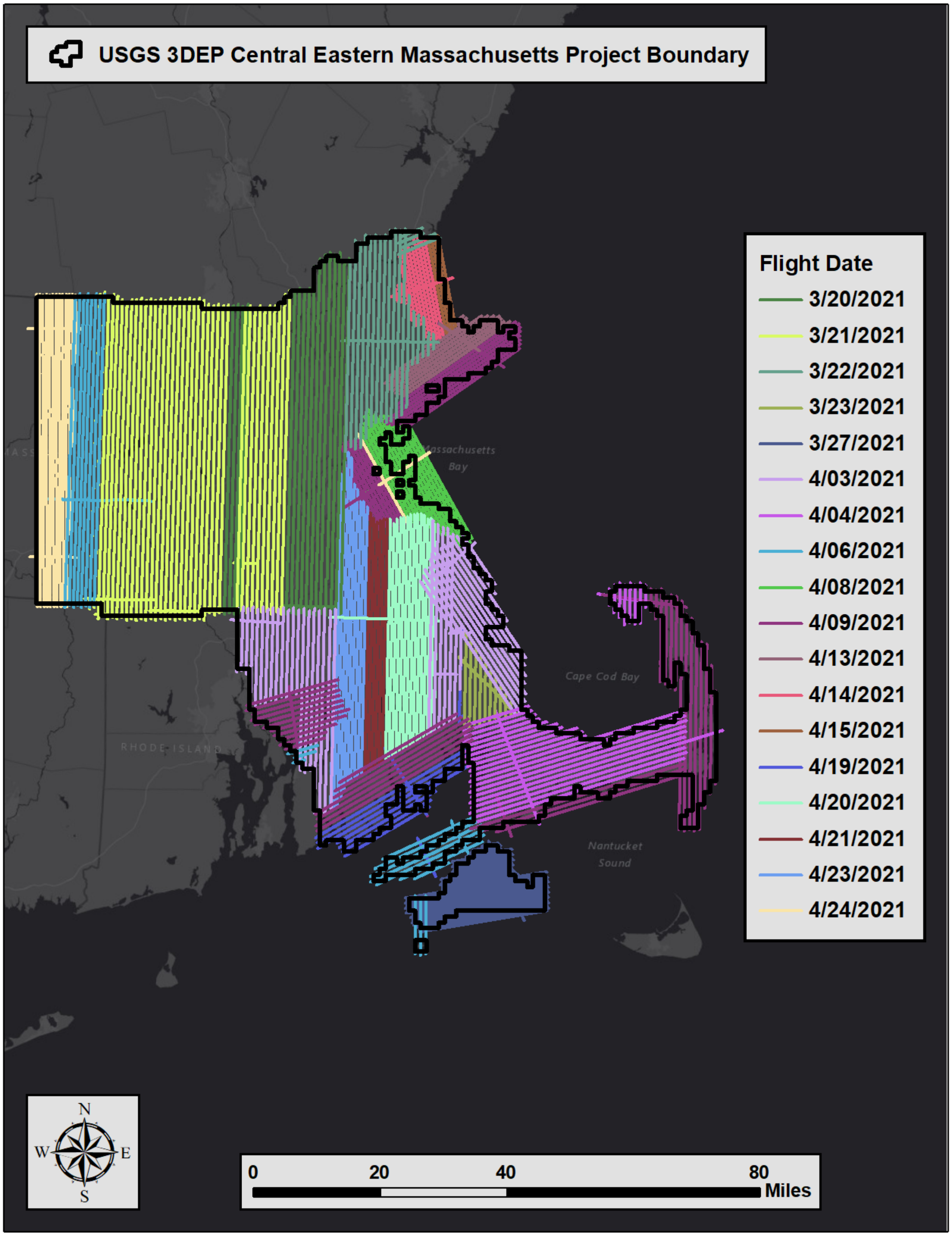


Figure 2: **Flightline Map**

Table 4: Lidar specifications and survey settings

Lidar Survey Settings & Specifications		
Acquisition Dates	March 20 – April 19, 2021	April 04 – April 24, 2021
Surveyor	NV5 Geospatial	SurvTech Solutions, Inc.
Aircraft Used	Cessna Caravan & Piper Navajo	Cessna Caravan
Sensor	Riegl	Optech
Laser	VQ-1560i	Galaxy-T2000
Maximum Returns	15	8
Resolution/Density	Average 8 pulses/m^2	Average 11 pulses/m^2
Nominal Pulse Spacing	0.35 m	0.30 m
Survey Altitude (AGL)	1,500 m	1,829 m
Survey speed	160 knots	120 knots
Field of View	58.52°	38°
Mirror Scan Rate	Uniform Point Spacing	95 Hz
Target Pulse Rate	1000 kHz	1100 kHz
Pulse Length	3.0 ns	2.5 ns
Laser Pulse Footprint Diameter	37.5 cm	42.0 cm
Central Wavelength	1064 nm	1064 nm
Pulse Mode	Multiple Times Around (MTA)	Multiple Pulses In AIR (MPIA)
Beam Divergence	0.25 mrad	0.23 mrad
Swath Width	1,681 m	1,259 m
Swath Overlap	20%	30%
Intensity	16-bit	12-bit scaled to 16-bit
Accuracy	$RMSE_Z$ (Non-Vegetated) ≤ 10 cm	
	NVA (95% Confidence Level) ≤ 19.6 cm	
	VVA (95^{th} Percentile) ≤ 30 cm	

All areas were surveyed with an opposing flight line side-lap of ≥20% (≥40% overlap) in order to reduce laser shadowing and increase surface laser painting. To accurately solve for laser point position (geographic coordinates x, y and z), the positional coordinates of the airborne sensor and the attitude of the aircraft were recorded continuously throughout the lidar data collection mission. Position of the aircraft was measured twice per second (2 Hz) by an onboard differential GPS unit, and aircraft attitude was measured 200 times per second (200 Hz) as pitch, roll and yaw (heading) from an onboard inertial measurement unit (IMU). To allow for post-processing correction and calibration, aircraft and sensor position and attitude data are indexed by GPS time.

Ground Survey

Ground control surveys, including monumentation and ground survey points (GSPs) were conducted by NV5 Geospatial to support the airborne acquisition. Ground control data were used to geospatially correct the aircraft positional coordinate data and to perform quality assurance checks on final lidar data products.

Base Stations

Base stations were utilized for collection of ground survey points using real time kinematic (RTK), fast static (FS), and total station (TS) survey techniques.

Monument locations were selected with consideration for satellite visibility, field crew safety, and optimal location for GSP coverage. NV5 Geospatial utilized 24 permanent real-time network (RTN) base stations from the KeyNet and SmartNet networks for the Central Eastern Massachusetts Lidar project (Table 5, Figure 3).

Table 5: Base station positions for the Central Eastern Massachusetts acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00

Monument ID	Network	Latitude	Longitude	Ellipsoid (meters)
ABL1	KeyNet	41°30'00.45537"	71°09'09.68777"	-5.975
CP01	KeyNet	42°49'28.33340"	71°24'59.77889"	50.988
KP10	KeyNet	41°39'04.60238"	70°14'51.45274"	-12.998
KP16	KeyNet	42°04'25.54584"	72°02'02.63763"	141.661
KPI6	KeyNet	42°09'15.81465"	71°29'34.06123"	69.960
NBC1	KeyNet	41°47'37.13299"	71°23'28.21265"	-1.900
NHCK	KeyNet	42°55'31.57802"	72°15'54.25361"	126.509
PTCS	KeyNet	42°03'03.38372"	70°11'30.72414"	-14.556
MABO	SmartNet	41°44'30.73952"	70°37'02.98095"	-16.621
MABR	SmartNet	42°12'36.39557"	70°59'37.91588"	-0.167
MAFB	SmartNet	42°34'26.06463"	71°47'33.20944"	131.970
MAFO	SmartNet	42°03'51.91333"	71°14'56.88999"	66.870
MAFR	SmartNet	42°18'00.17287"	71°26'30.86318"	44.294
MANT	SmartNet	41°15'47.53653"	70°03'40.03326"	-9.934
MAOR	SmartNet	41°46'34.41820"	70°00'26.82181"	-10.963
MAPY	SmartNet	41°57'04.63196"	70°42'40.58981"	20.27
MARR	SmartNet	42°39'06.64481"	70°36'36.05879"	6.605

Monument ID	Network	Latitude	Longitude	Ellipsoid (meters)
MATN	SmartNet	41°54'33.70357"	71°03'17.32738"	-13.226
MAWB	SmartNet	42°29'00.56595"	71°09'29.64729"	9.841
MAWE	SmartNet	42°15'06.88811"	71°48'18.22647"	117.024
NHNU	SmartNet	42°44'50.13959"	71°29'21.54646"	35.01
NHPM	SmartNet	43°02'34.61765"	70°46'29.12499"	-2.349
RIKT	SmartNet	41°35'17.18714"	71°25'49.31527"	-13.918
RILN	SmartNet	41°56'12.76432"	71°27'38.42207"	76.335

NV5 Geospatial utilized static Global Navigation Satellite System (GNSS) data collected at 1 Hz recording frequency for each base station. During post-processing, the static GNSS data were triangulated with nearby Continuously Operating Reference Stations (CORS) using the Online Positioning User Service (OPUS[1]) for precise positioning. Multiple independent sessions over the same monument were processed to confirm antenna height measurements and to refine position accuracy.

Ground Survey Points (GSPs)

Ground survey points were collected using real time kinematic (RTK), fast-static (FS), and total station (TS) survey techniques. For RTK surveys, a roving receiver receives corrections from a nearby base station or Real-Time Network (RTN) via radio or cellular network, enabling rapid collection of points with relative errors less than 1.5 cm horizontal and 2.0 cm vertical. FS surveys compute these corrections during post-processing to achieve comparable accuracy. RTK surveys record data while stationary for at least five seconds, calculating the position using at least three one-second epochs. FS surveys record observations for up to fifteen minutes on each GSP in order to support longer baselines. All GSP measurements were made during periods with a Position Dilution of Precision (PDOP) of ≤ 3.0 with at least six satellites in view of the stationary and roving receivers. See Table 6 for Trimble unit specifications.

Forested check points are collected using total stations in order to measure positions under dense canopy. Total station backsight and setup points are established using GNSS survey techniques.

GSPs were collected in areas where good satellite visibility was achieved on paved roads and other hard surfaces such as gravel or packed dirt roads. GSP measurements were not taken on highly reflective surfaces such as center line stripes or lane markings on roads due to the increased noise seen in the laser returns over these surfaces. GSPs were collected within as many flightlines as possible; however, the distribution of GSPs depended on ground access constraints and monument locations and may not be equitably distributed throughout the study area (Figure 3).

[1] OPUS is a free service provided by the National Geodetic Survey to process corrected monument positions. http://www.ngs.noaa.gov/OPUS.

Table 6: NV5 Geospatial ground survey equipment identification

Receiver Model	Antenna	OPUS Antenna ID	Use
Trimble R8 Model 2	Integrated Antenna	TRMR8_GNSS	Rover
Trimble M3 Total Station		n/a	VVA

Land Cover Class

In addition to ground survey points, land cover class check points were collected throughout the study area to evaluate vertical accuracy. Vertical accuracy statistics were calculated for all land cover types to assess confidence in the lidar derived ground models across land cover classes (Table 7, see Lidar Accuracy Assessments, page 24).

Table 7: Land Cover Types and Descriptions

Land cover type	Example	Description	Accuracy Assessment Type
Shrub/ Brushland		Maintained or herbaceous low growth	VVA
Tall Grass/Weeds		Herbaceous grasslands in advanced stages of growth	VVA
Forest		Mixed forested areas	VVA
Bare Earth		Areas of bare earth surface	NVA
Urban		Areas dominated by urban development, including parks	NVA

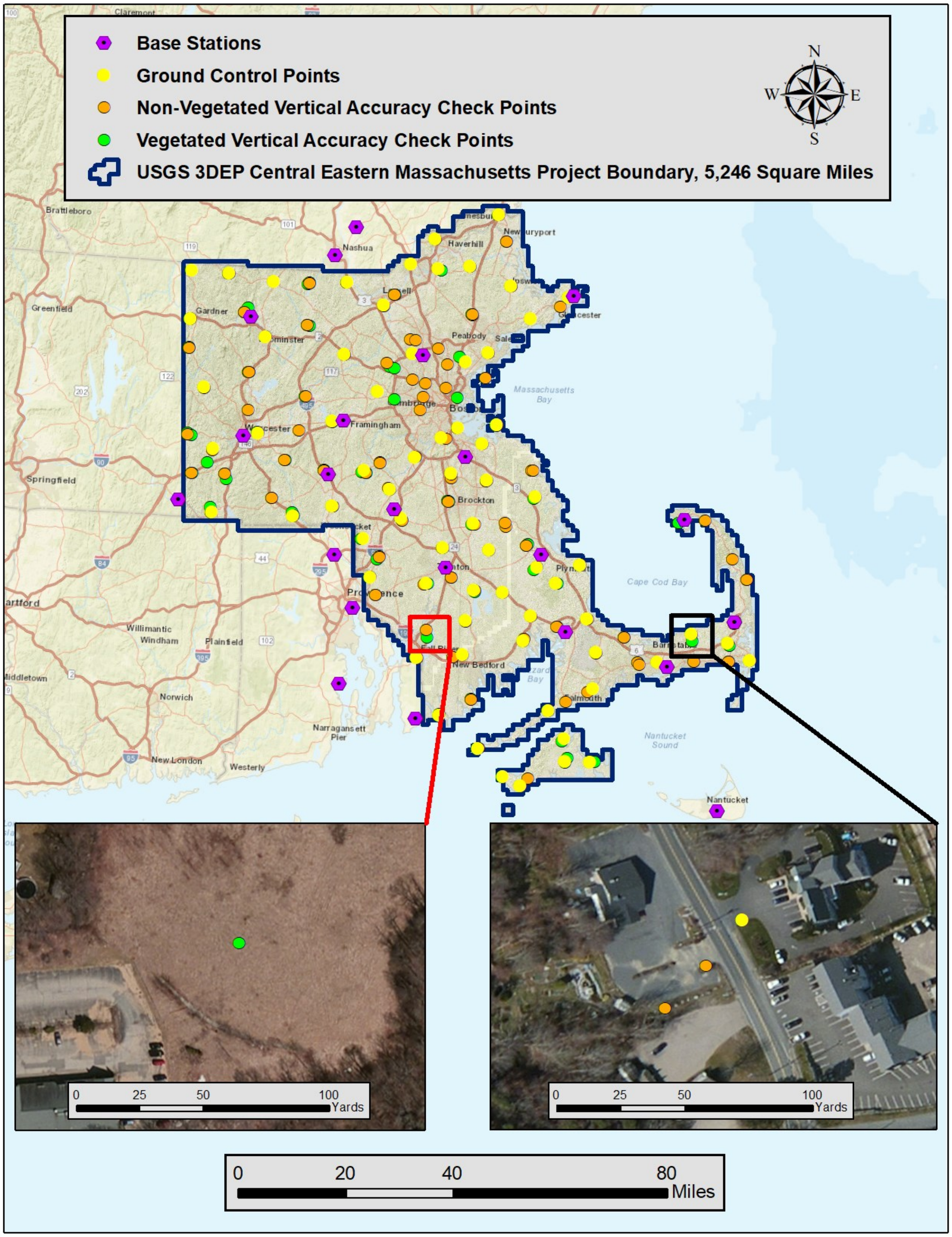
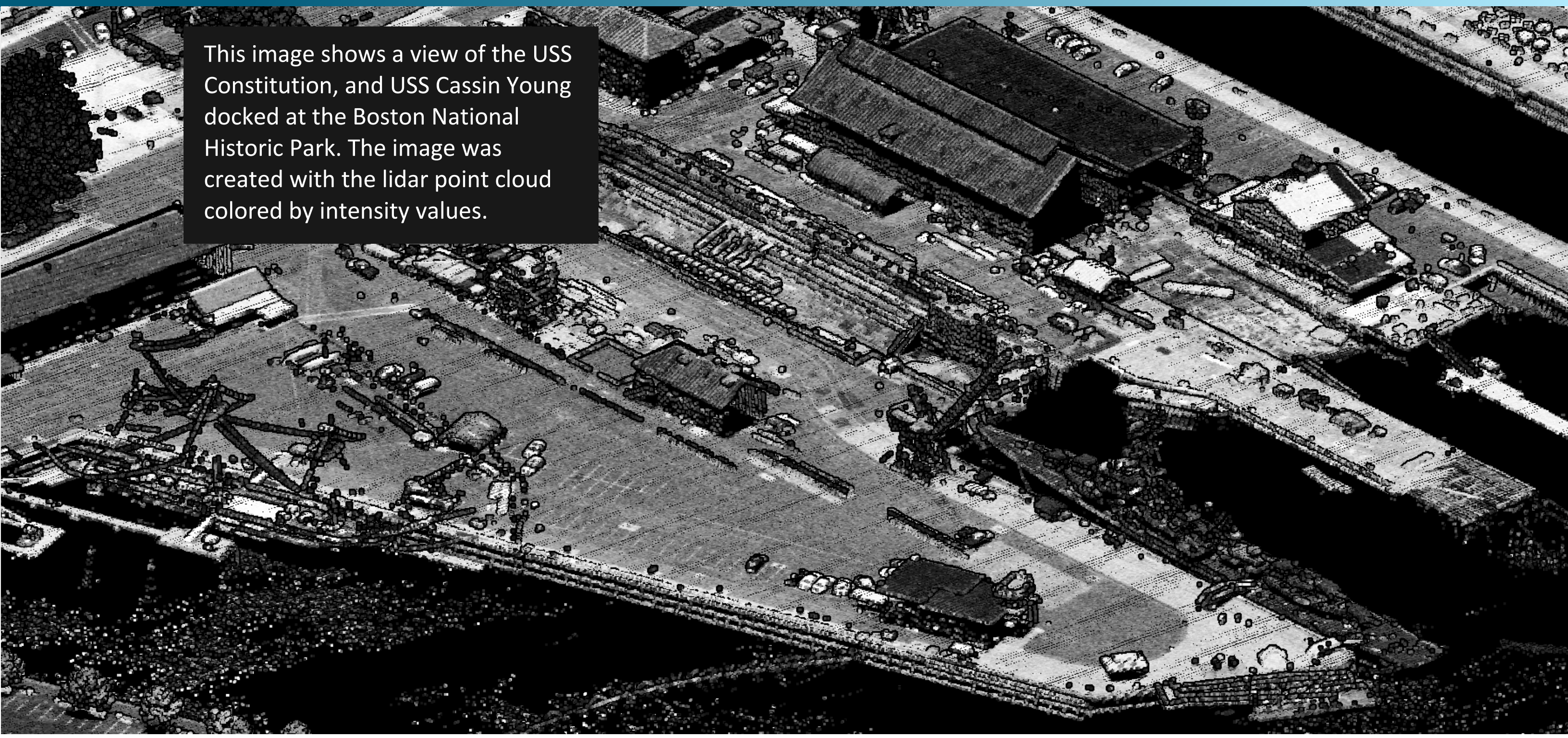


Figure 3: Ground survey location map

PROCESSING



This image shows a view of the USS Constitution, and USS Cassin Young docked at the Boston National Historic Park. The image was created with the lidar point cloud colored by intensity values.

Lidar Data

Upon completion of data acquisition, NV5 Geospatial processing staff initiated a suite of automated and manual techniques to process the data into the requested deliverables. Processing tasks included GPS control computations, smoothed best estimate trajectory (SBET) calculations, kinematic corrections, calculation of laser point position, sensor and data calibration for optimal relative and absolute accuracy, and lidar point classification (Table 8). Processing methodologies were tailored for the landscape. Brief descriptions of these tasks are shown in Table 9.

Table 8: ASPRS LAS classification standards applied to the Central Eastern Massachusetts dataset

Classification Number	Classification Name	Classification Description
1	Default/Unclassified	Laser returns that are not included in the ground class, composed of vegetation and anthropogenic features
2	Ground	Laser returns that are determined to be ground using automated and manual cleaning algorithms
3	Low Vegetation	Any vegetation within 0.5 and 2 meters of the ground surface
4	Medium Vegetation	Any vegetation between 2 – 5 meters above the ground surface
5	High Vegetation	Any vegetation greater than 5 meters above the ground surface
6	Buildings	Permanent structures such as buildings
7-W	Low Noise (Withheld)	Laser returns that are often associated with artificial points below the ground surface
9	Water	Laser returns that are determined to be water using automated and manual cleaning algorithms
17	Bridge	Bridge decks
18-W	High Noise (Withheld)	Laser returns that are often associated with birds, or scattering from reflective surfaces.
20	Ignored Ground	Ground points proximate to water's edge breaklines; ignored for correct model creation
22	Temporal exclusion	Non-favored data in intertidal zones

Table 9: Lidar Processing Workflow

Lidar Processing Step	Software Used
Resolve kinematic corrections for aircraft position data using kinematic aircraft GPS and static ground GPS data. Develop a smoothed best estimate of trajectory (SBET) file that blends post-processed aircraft position with sensor head position and attitude recorded throughout the survey.	POSPac MMS v.8.5 POFImport 1.7.4
Calculate laser point position by associating SBET position to each laser point return time, scan angle, intensity, etc. Create raw laser point cloud data for the entire survey in *.las (ASPRS v. 1.4) format. Convert data to orthometric elevations by applying a geoid correction.	GeoRun v.6.1.1 TerraMatch v.19
Using ground classified points per each flight line, test the relative accuracy. Perform automated line-to-line calibrations for system attitude parameters (pitch, roll, heading), mirror flex (scale) and GPS/IMU drift. Calculate calibrations on ground classified points from paired flight lines and apply results to all points in a flight line. Use every flight line for relative accuracy calibration.	BayesMap-StripAlign v.2.19
Import calibrated points into manageable blocks for editing	TerraScan v.19.005
Classify resulting data to ground and other client designated ASPRS classifications (Table 10). Assess statistical absolute accuracy via direct comparisons of ground classified points to ground control survey data.	TerraScan v.19.005 TerraModeler v.19.003
Generate bare earth models as triangulated surfaces. Generate highest hit models as a surface expression of all classified points. Export all surface models as Cloud Optimized GeoTIFFs at a 0.5-meter pixel resolution.	LAS Product Creator v.3.5 (NV5 Geospatial proprietary) ArcMap v. 10.8.1
Correct intensity values for variability and export intensity images as Cloud Optimized GeoTIFFs at a 0.5-meter pixel resolution.	LAS Product Creator v.3.5 (NV5 Geospatial proprietary) ArcMap v. 10.8.1

Feature Extraction

Hydroflattening and Water's Edge Breaklines

Cape Cod and all tidal waterbodies surrounding the Central Eastern Massachusetts project area as well as rivers and lakes within the project area were flattened to a consistent water level. Bodies of water that were flattened include lakes and other closed water bodies with a surface area greater than 1 acres, all streams and rivers that are nominally wider than 15 meters, all non-tidal waters bordering the project, and select smaller bodies of water as feasible. The hydroflattening process eliminates artifacts in the digital terrain model caused by both increased variability in ranges or dropouts in laser returns due to the low reflectivity of water.

Hydroflattening of closed water bodies was performed through a combination of automated and manual detection and adjustment techniques designed to identify water boundaries and water levels. Boundary polygons were developed using an algorithm which weights lidar-derived slopes, intensities, and return densities to detect the water's edge. The water edges were then manually reviewed and edited as necessary. Specific care was taken to not hydroflatten wetland and marsh habitat found throughout the study site.

Once polygons were developed the initial ground classified points falling within water polygons were reclassified as water points to omit them from the final ground model. Elevations were then obtained from the filtered lidar returns to create the final breaklines. Lakes were assigned a consistent elevation for an entire polygon while rivers were assigned consistent elevations on opposing banks and smoothed to ensure downstream flow through the entire river channel.

Water boundary breaklines were then incorporated into the hydroflattened DEM by enforcing triangle edges (adjacent to the breakline) to the elevation values of the breakline. This implementation corrected interpolation along the hard edge. Water surfaces were obtained from a TIN of the 3-D water edge breaklines resulting in the final hydroflattened model (Figure 4).

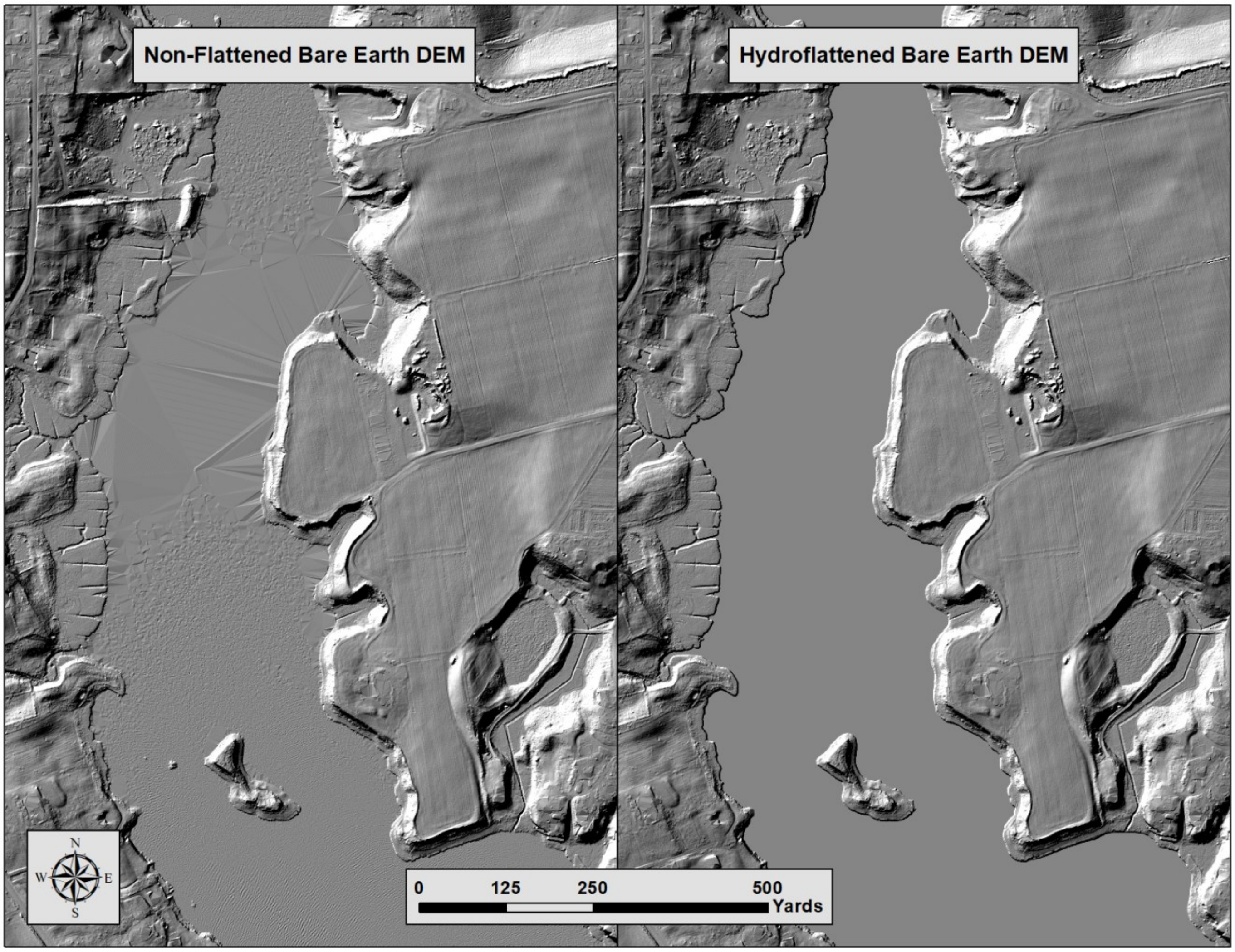
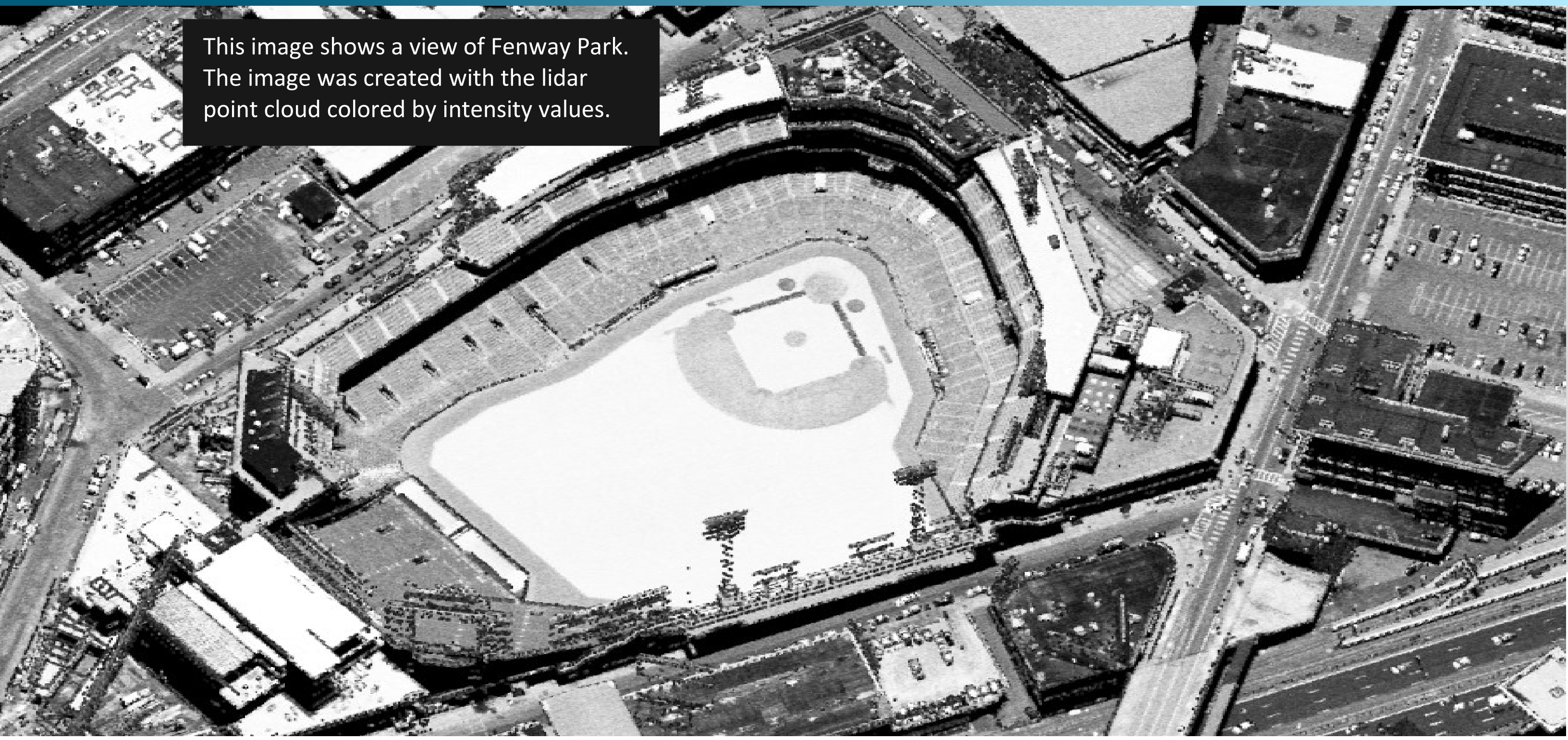


Figure 4: Example of hydroflattening in the Central Eastern Massachusetts Lidar dataset



This image shows a view of Fenway Park. The image was created with the lidar point cloud colored by intensity values.

Lidar Density

The acquisition parameters were designed to acquire an average first-return density of 8 points/m^2. First return density describes the density of pulses emitted from the laser that return at least one echo to the system. Multiple returns from a single pulse were not considered in first return density analysis. Some types of surfaces (e.g., breaks in terrain, water and steep slopes) may have returned fewer pulses than originally emitted by the laser. First returns typically reflect off the highest feature on the landscape within the footprint of the pulse. In forested or urban areas the highest feature could be a tree, building or power line, while in areas of unobstructed ground, the first return will be the only echo and represents the bare earth surface.

The density of ground-classified lidar returns was also analyzed for this project. Terrain character, land cover, and ground surface reflectivity all influenced the density of ground surface returns. In vegetated areas, fewer pulses may penetrate the canopy, resulting in lower ground density.

The average first-return density of lidar data for the Central Eastern Massachusetts project was 13.75 points/m^2 while the average ground classified density was 8.15 points/m^2 (Table 10). The statistical and spatial distributions of first return densities and classified ground return densities per 100 m x 100 m cell are portrayed in Figure 5 through Figure 8.

Table 10: Average lidar point densities

Classification	Point Density
First-Return	13.75 points/m^2
Ground Classified	8.15 points/m^2

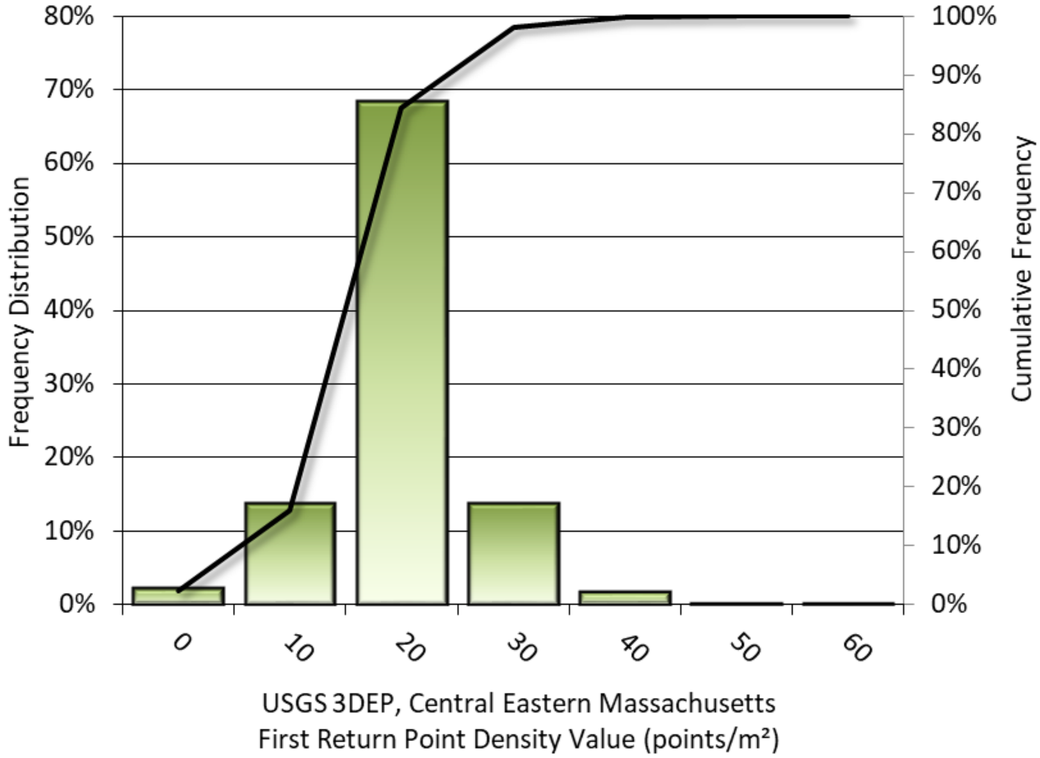


Figure 5: Frequency distribution of first return point density values per 100 x 100 m cell

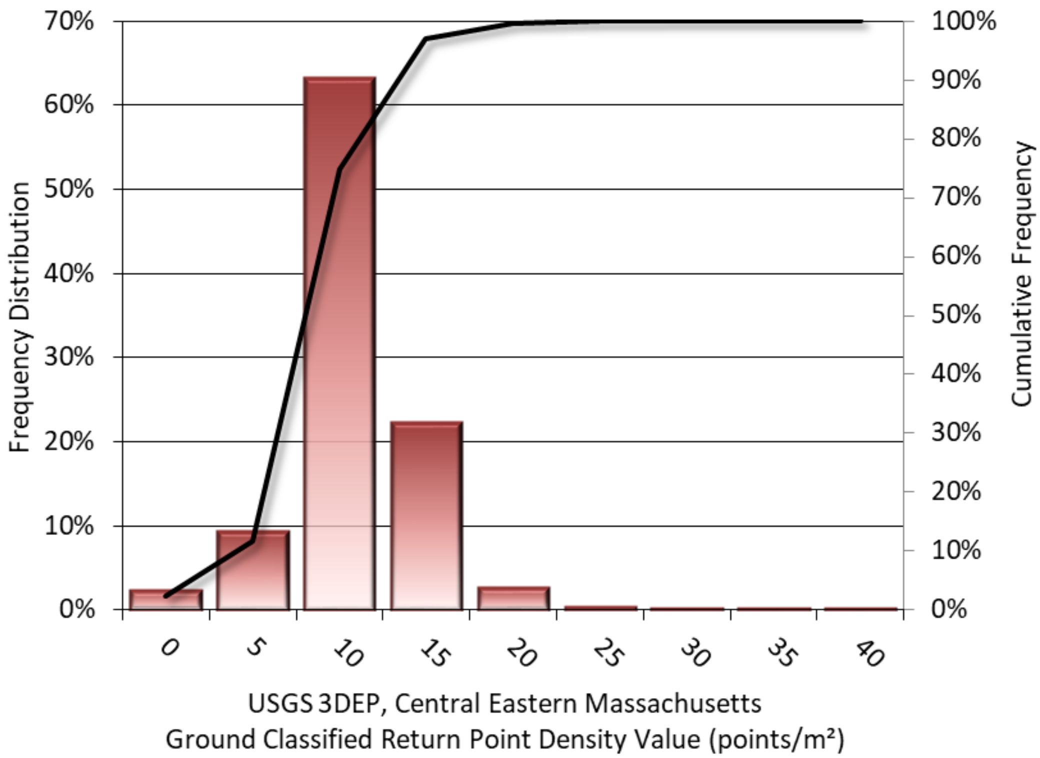


Figure 6: Frequency distribution of ground-classified return point density values per 100 x 100 m cell

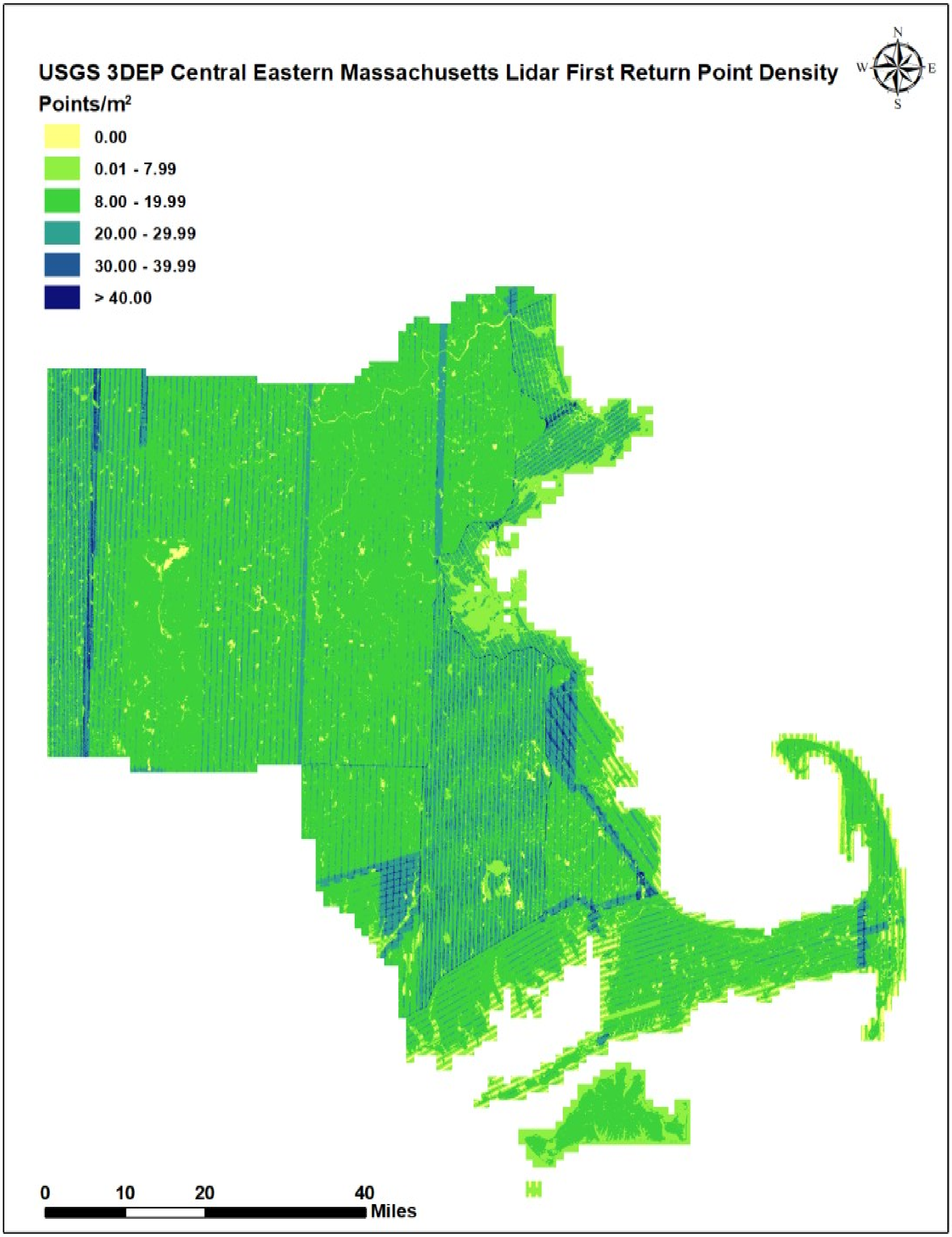


Figure 7: First return point density map for the Central Eastern Massachusetts project area (100 m x 100 m cells)

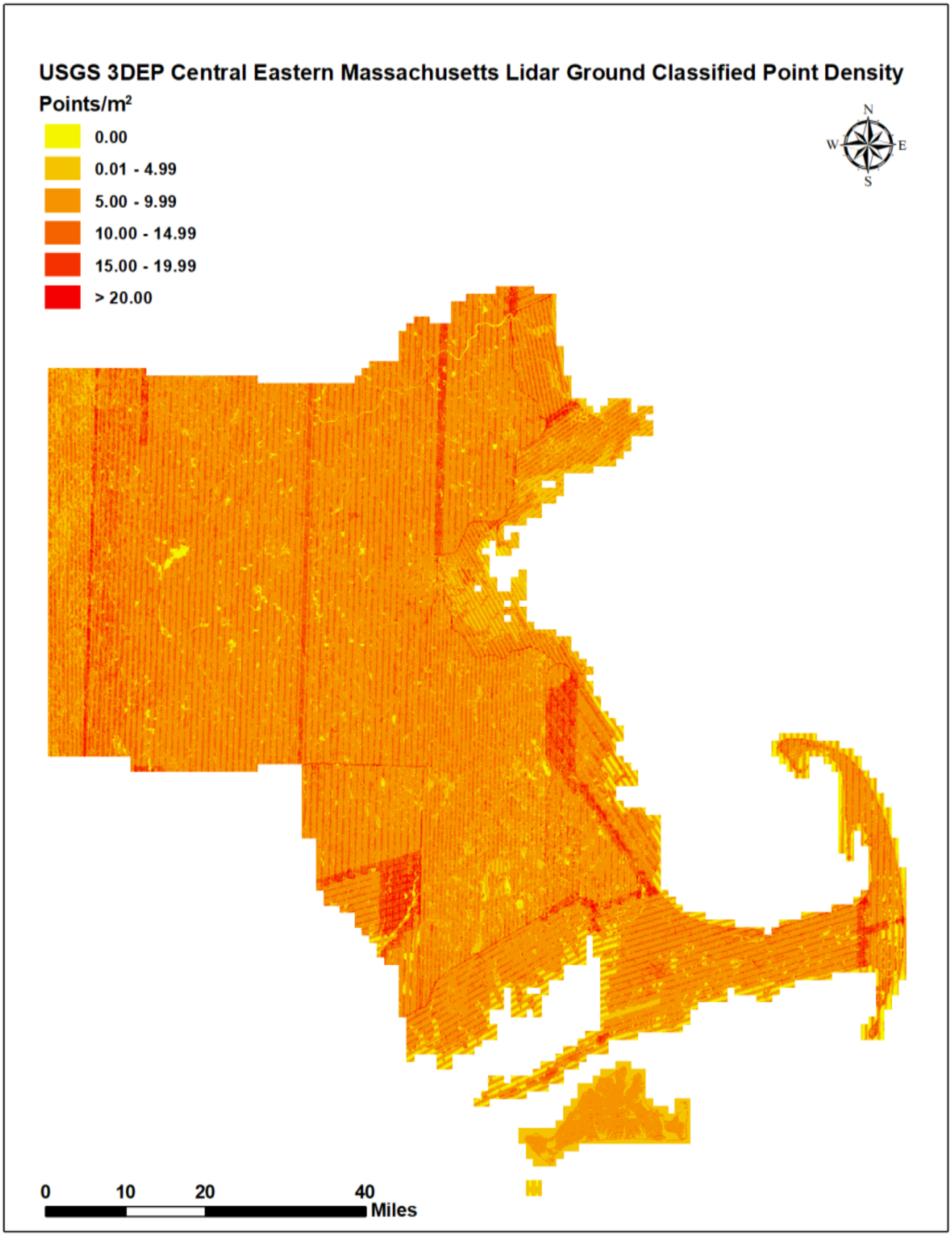


Figure 8: Ground point density map for the Central Eastern Massachusetts project area (100 m x 100 m cells)

Lidar Accuracy Assessments

The accuracy of the lidar data collection can be described in terms of absolute accuracy (the consistency of the data with external data sources) and relative accuracy (the consistency of the dataset with itself). See Appendix A for further information on sources of error and operational measures used to improve relative accuracy.

Lidar Non-Vegetated Vertical Accuracy

Absolute accuracy was assessed using Non-Vegetated Vertical Accuracy (NVA) reporting designed to meet guidelines presented in the FGDC National Standard for Spatial Data Accuracy[2]. NVA compares known ground check point data that were withheld from the calibration and post-processing of the lidar point cloud to the triangulated surface generated by the classified lidar point cloud as well as the derived gridded bare earth DEM. NVA is a measure of the accuracy of lidar point data in open areas where the lidar system has a high probability of measuring the ground surface and is evaluated at the 95% confidence interval (1.96 * RMSE), as shown in Table 11.

The mean and standard deviation (sigma σ) of divergence of the ground surface model from quality assurance point coordinates are also considered during accuracy assessment. These statistics assume the error for x, y and z is normally distributed, and therefore the skew and kurtosis of distributions are also considered when evaluating error statistics. For the Central Eastern Massachusetts survey, 129 ground check points were withheld from the calibration and post processing of the lidar point cloud, with resulting non-vegetated vertical accuracy of 0.074 meters as compared to classified LAS, and 0.075 meters as compared to the bare earth DEM, with 95% confidence (Figure 9, Figure 10).

NV5 Geospatial also assessed absolute accuracy using 70 ground control points. Although these points were used in the calibration and post-processing of the lidar point cloud, they still provide a good indication of the overall accuracy of the lidar dataset, and therefore have been provided in Table 11 and Figure 11.

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[2] Federal Geographic Data Committee, ASPRS POSITIONAL ACCURACY STANDARDS FOR DIGITAL GEOSPATIAL DATA EDITION 1, Version 1.0, NOVEMBER 2014. https://www.asprs.org/a/society/committees/standards/Positional_Accuracy_Standards.pdf.

Table 11: Absolute accuracy results

Absolute Vertical Accuracy			
	NVA, as compared to classified LAS	**NVA, as compared to bare earth DEM**	**Ground Control Points**
Sample	129 points	129 points	70 points
95% Confidence (1.96*RMSE)	0.074 m	0.075 m	0.068 m
Average	0.001 m	0.000 m	-0.006 m
Median	0.002 m	0.001 m	-0.004 m
RMSE	0.038 m	0.038 m	0.035 m
Standard Deviation (1σ)	0.038 m	0.038 m	0.034 m

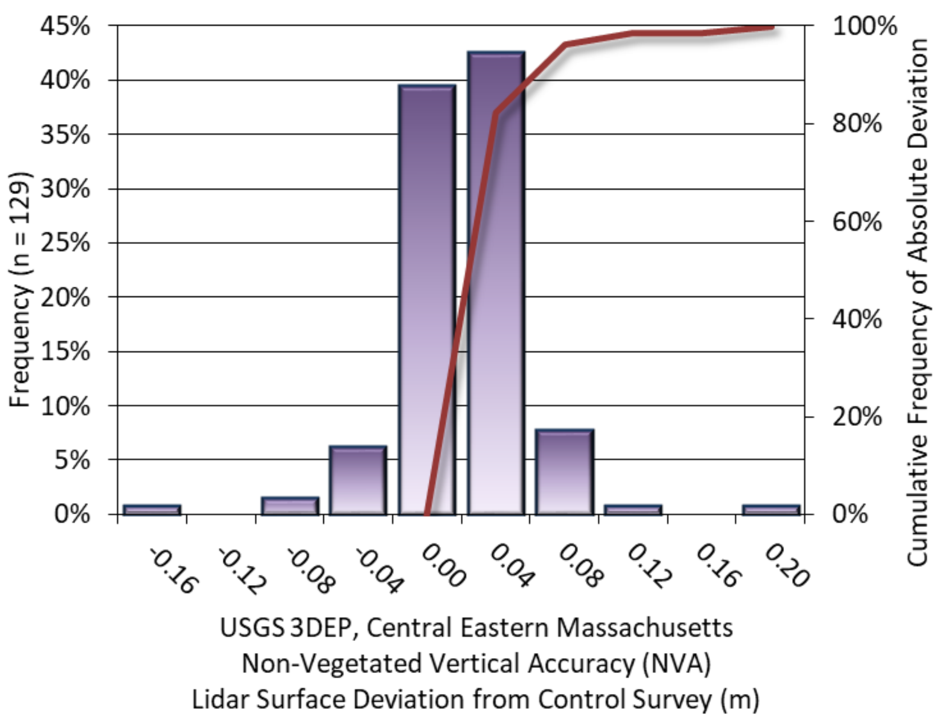

Figure 9: Frequency histogram for lidar classified LAS deviation from ground check point values (NVA)

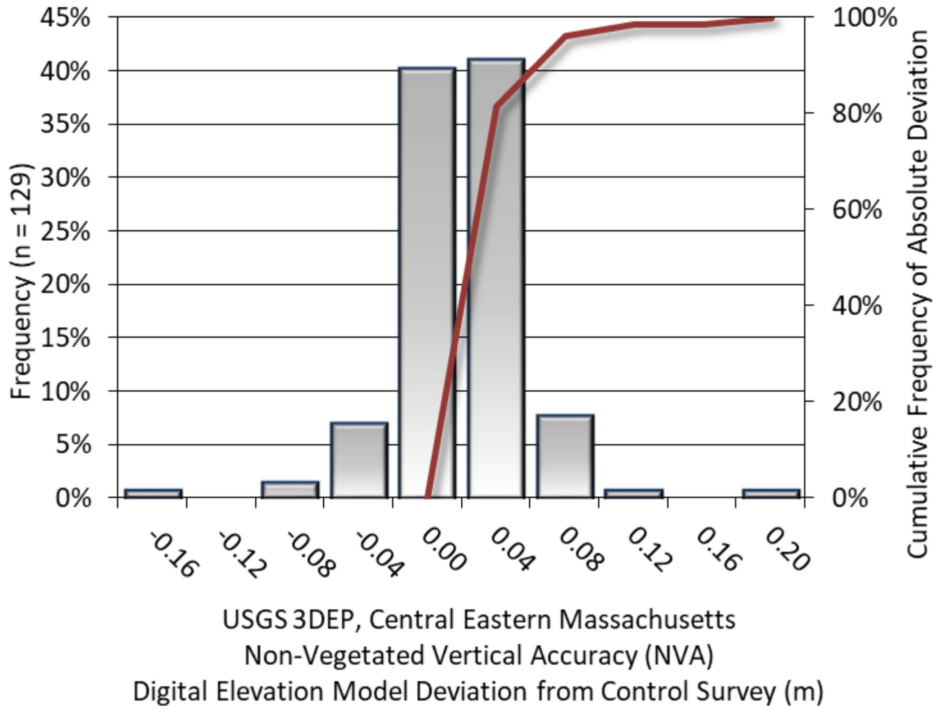

Figure 10: Frequency histogram for the lidar bare earth DEM surface deviation from ground check point values (NVA)

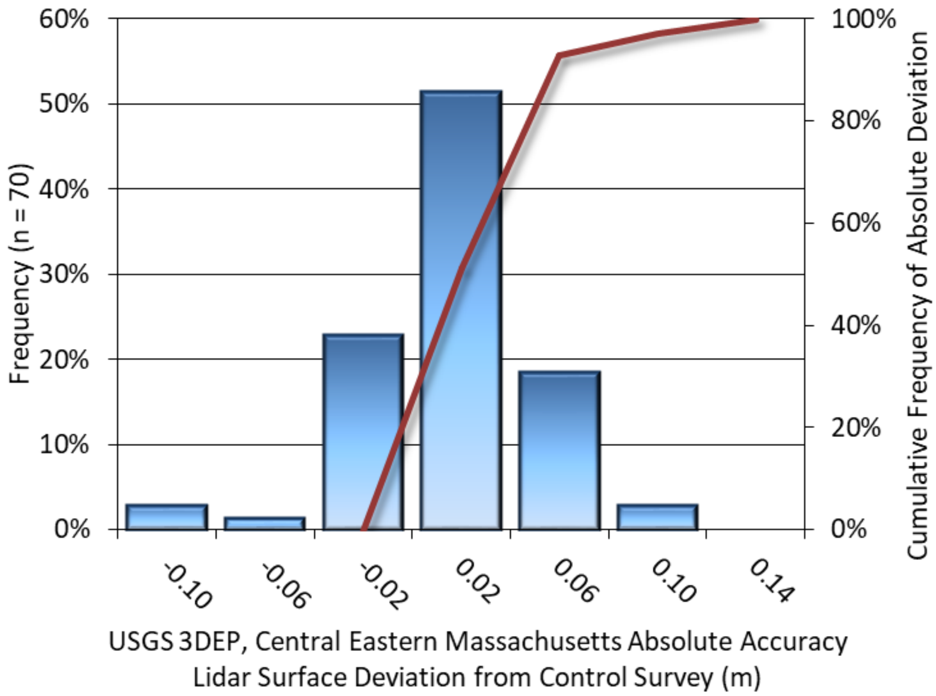

Figure 11: Frequency histogram the for lidar surface deviation from ground control point values

Lidar Vegetated Vertical Accuracies

NV5 Geospatial also assessed vertical accuracy using Vegetated Vertical Accuracy (VVA) reporting. VVA compares known ground check point data collected over vegetated surfaces using land class descriptions to the triangulated ground surface generated by the ground classified lidar points. For the Central Eastern Massachusetts survey, 95 vegetated check points were collected, with resulting vegetated vertical accuracy of 0.136 meters as compared to the classified LAS, and 0.126 meters as compared to the bare earth DEM evaluated at the 95th percentile (Table 12, Figure 12).

Table 12: Vegetated vertical accuracy results

Vegetated Vertical Accuracy		
	VVA, as compared to classified LAS	VVA, as compared to bare earth DEM
Sample	95 points	95 points
95th Percentile	0.136 m	0.126 m
Average	0.040 m	0.043 m
Median	0.038 m	0.041 m
RMSE	0.068 m	0.072 m
Standard Deviation (1σ)	0.055 m	0.058 m

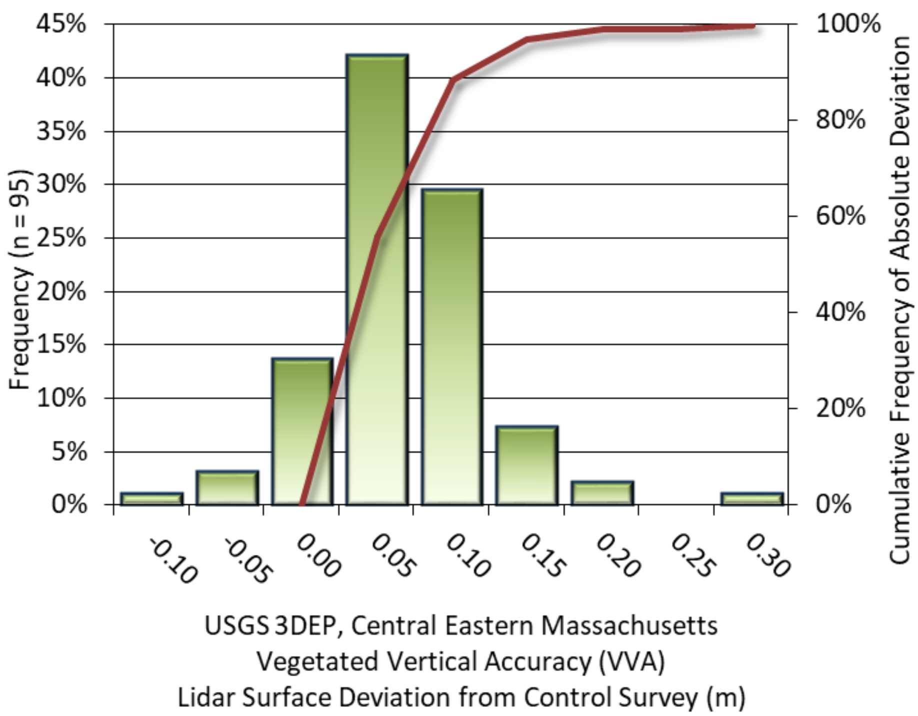

Figure 12: Frequency histogram for the lidar surface deviation from vegetated check point values (VVA)

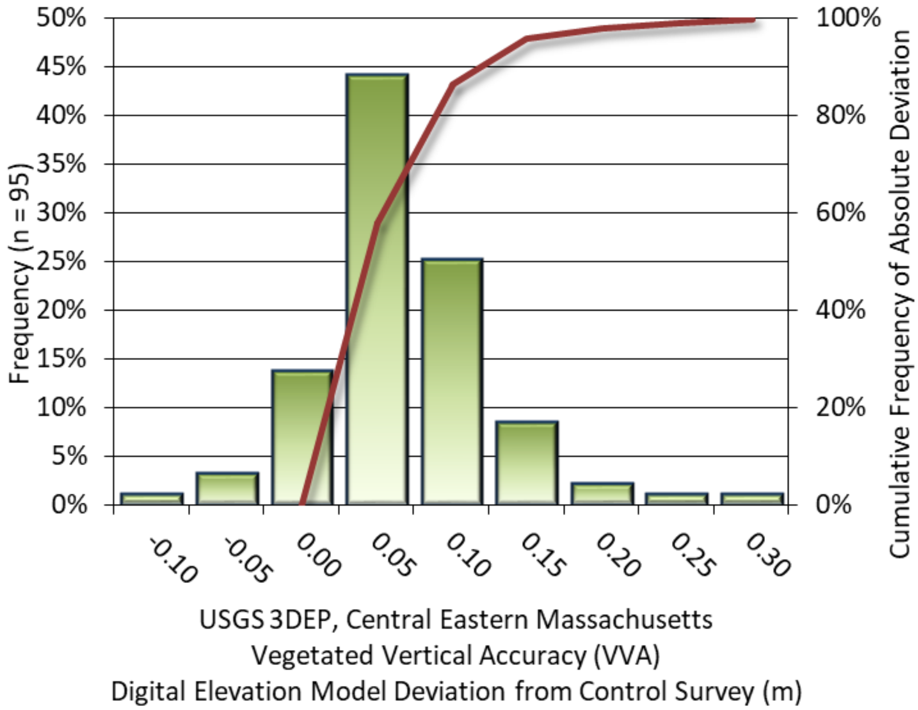

Figure 13: Frequency histogram for the lidar bare earth DEM deviation from vegetated check point values (VVA)

Lidar Relative Vertical Accuracy

Relative vertical accuracy refers to the internal consistency of the data set as a whole: the ability to place an object in the same location given multiple flight lines, GPS conditions, and aircraft attitudes. When the lidar system is well calibrated, the swath-to-swath vertical divergence is low (<0.10 meters). The relative vertical accuracy was computed by comparing the ground surface model of each individual flight line with its neighbors in overlapping regions. The average (mean) line to line relative vertical accuracy for the Central Eastern Massachusetts Lidar project was 0.011 meters (Table 13, Figure 14).

Table 13: Relative accuracy results

Relative Accuracy	
Sample	345 surfaces
Average	0.011 m
Median	0.011 m
RMSE	0.011 m
Standard Deviation (1σ)	0.003 m
1.96σ	0.005 m

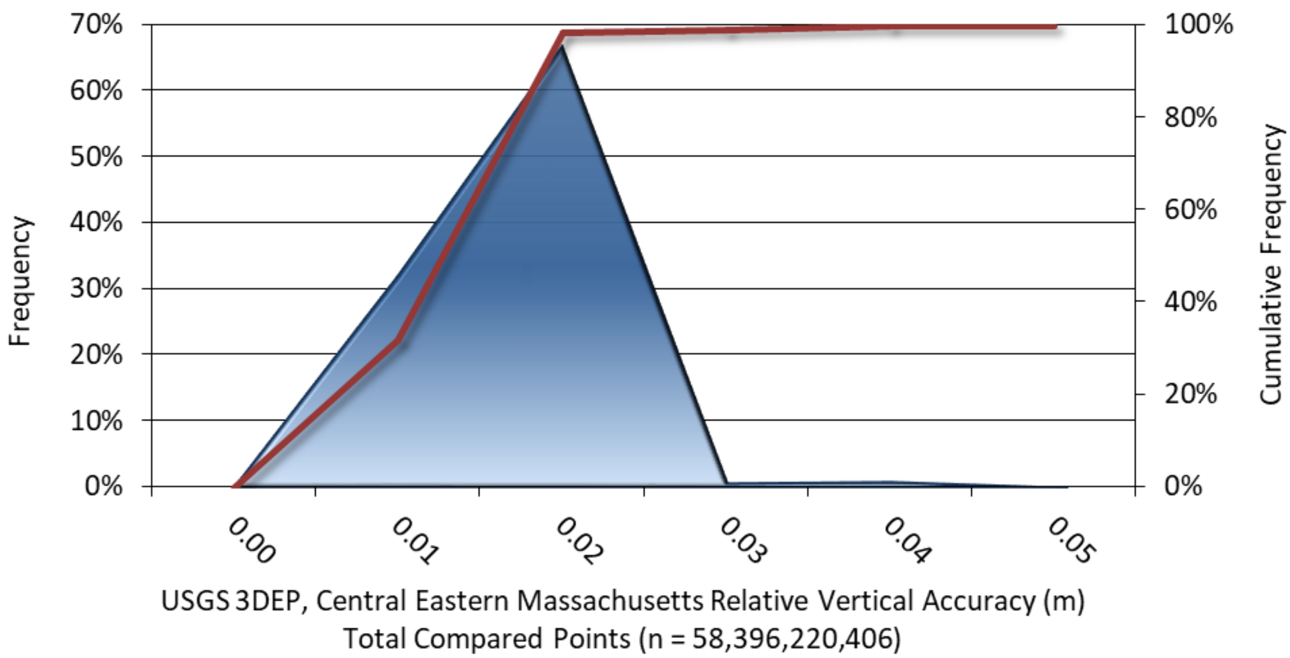

Figure 14: Frequency plot for relative vertical accuracy between flight lines

Lidar Horizontal Accuracy

Lidar horizontal accuracy is a function of Global Navigation Satellite System (GNSS) derived positional error, flying altitude, and INS derived attitude error. The obtained $RMSE_r$ value is multiplied by a conversion factor of 1.7308 to yield the horizontal component of the National Standards for Spatial Data Accuracy (NSSDA) reporting standard where a theoretical point will fall within the obtained radius 95 percent of the time. All areas surveyed at a flying altitude of 1,500 meters, with an IMU error of 0.002 decimal degrees, and a GNSS positional error of 0.015 meters, were produced to meet 0.16 m horizontal accuracy at the 95% confidence level. All areas surveyed at a flying altitude of 1,829 meters, with an IMU error of 0.002 decimal degrees, and a GNSS positional error of 0.015 meters, were produced to meet 0.20 m horizontal accuracy at the 95% confidence level.

Table 14: Horizontal Accuracy at 1,500 m flying altitude

Horizontal Accuracy	
$RMSE_r$	0.09 m
ACC_r	0.16 m

Table 15: Horizontal Accuracy at 1,829 m flying altitude

Horizontal Accuracy	
$RMSE_r$	0.11 m
ACC_r	0.20 m

CERTIFICATIONS

NV5 Geospatial provided lidar services for the Central Eastern Massachusetts project as described in this report.

I, Christopher Holder, have reviewed the attached report for completeness and hereby state that it is a complete and accurate report of this project.

Christopher Holder
Christopher Holder (Jan 28, 2022 17:27 EST)

Jan 28, 2022

Christopher Holder
Project Manager
NV5 Geospatial

I, Kevin Blake, being a Licensed Professional Land Surveyor in the State of Massachusetts, hereby certify to the best of my professional knowledge and belief that the survey methodologies and results shown on the attached report for the State portion of the report titled USGS 3DEP Central Eastern Massachusetts Lidar Technical Data Report, dated January 26, 2022, were performed, and obtained utilizing commonly acceptable survey standards, practices and procedures. The survey portion of this project was accomplished between April 13, 2021 through May 09, 2021. The aerial LiDAR was obtained between March 20, 2021 through April 24, 2021.

I have reviewed the accuracy statements as part of my oversight and found them to meet the National Standards for Spatial Accuracy (NSSDA) shown.

Kevin Blake MALS # 46824

GLOSSARY

1-sigma (σ) Absolute Deviation: Value for which the data are within one standard deviation (approximately 68th percentile) of a normally distributed data set.

1.96 * RMSE Absolute Deviation: Value for which the data are within two standard deviations (approximately 95th percentile) of a normally distributed data set, based on the FGDC standards for Non-vegetated Vertical Accuracy (NVA) reporting.

Accuracy: The statistical comparison between known (surveyed) points and laser points. Typically measured as the standard deviation (sigma σ) and root mean square error (RMSE).

> **Absolute Accuracy:** The vertical accuracy of lidar data is described as the mean and standard deviation (sigma σ) of divergence of lidar point coordinates from ground survey point coordinates. To provide a sense of the model predictive power of the dataset, the root mean square error (RMSE) for vertical accuracy is also provided. These statistics assume the error distributions for x, y and z are normally distributed, and thus we also consider the skew and kurtosis of distributions when evaluating error statistics.
>
> **Relative Accuracy:** Relative accuracy refers to the internal consistency of the data set; i.e., the ability to place a laser point in the same location over multiple flight lines, GPS conditions and aircraft attitudes. Affected by system attitude offsets, scale and GPS/IMU drift, internal consistency is measured as the divergence between points from different flight lines within an overlapping area. Divergence is most apparent when flight lines are opposing. When the lidar system is well calibrated, the line-to-line divergence is low (<10 cm).
>
> **Root Mean Square Error (RMSE):** A statistic used to approximate the difference between real-world points and the lidar points. It is calculated by squaring all the values, then taking the average of the squares and taking the square root of the average.

Data Density: A common measure of lidar resolution, measured as points per square meter.

Digital Elevation Model (DEM): File or database made from surveyed points, containing elevation points over a contiguous area. Digital terrain models (DTM) and digital surface models (DSM) are types of DEMs. DTMs consist solely of the bare earth surface (ground points), while DSMs include information about all surfaces, including vegetation and man-made structures.

Intensity Values: The peak power ratio of the laser return to the emitted laser, calculated as a function of surface reflectivity.

Nadir: A single point or locus of points on the surface of the earth directly below a sensor as it progresses along its flight line.

Overlap: The area shared between flight lines, typically measured in percent. 100% overlap is essential to ensure complete coverage and reduce laser shadows.

Pulse Rate (PR): The rate at which laser pulses are emitted from the sensor; typically measured in thousands of pulses per second (kHz).

Pulse Returns: For every laser pulse emitted, the number of wave forms (i.e., echoes) reflected back to the sensor. Portions of the wave form that return first are the highest element in multi-tiered surfaces such as vegetation. Portions of the wave form that return last are the lowest element in multi-tiered surfaces.

Real-Time Kinematic (RTK) Survey: A type of surveying conducted with a GPS base station deployed over a known monument with a radio connection to a GPS rover. Both the base station and rover receive differential GPS data and the baseline correction is solved between the two. This type of ground survey is accurate to 1.5 cm or less.

Post-Processed Kinematic (PPK) Survey: GPS surveying is conducted with a GPS rover collecting concurrently with a GPS base station set up over a known monument. Differential corrections and precisions for the GNSS baselines are computed and applied after the fact during processing. This type of ground survey is accurate to 1.5 cm or less.

Scan Angle: The angle from nadir to the edge of the scan, measured in degrees. Laser point accuracy typically decreases as scan angles increase.

Native Lidar Density: The number of pulses emitted by the lidar system, commonly expressed as pulses per square meter.

Relative Accuracy Calibration Methodology:

Manual System Calibration: Calibration procedures for each mission require solving geometric relationships that relate measured swath-to-swath deviations to misalignments of system attitude parameters. Corrected scale, pitch, roll and heading offsets were calculated and applied to resolve misalignments. The raw divergence between lines was computed after the manual calibration was completed and reported for each survey area.

Automated Attitude Calibration: All data were tested and calibrated using TerraMatch automated sampling routines. Ground points were classified for each individual flight line and used for line-to-line testing. System misalignment offsets (pitch, roll and heading) and scale were solved for each individual mission and applied to respective mission datasets. The data from each mission were then blended when imported together to form the entire area of interest.

Automated Z Calibration: Ground points per line were used to calculate the vertical divergence between lines caused by vertical GPS drift. Automated Z calibration was the final step employed for relative accuracy calibration.

Lidar accuracy error sources and solutions:

Type of Error	Source	Post Processing Solution
GPS (Static/Kinematic)	Long Base Lines	None
	Poor Satellite Constellation	None
	Poor Antenna Visibility	Reduce Visibility Mask
Relative Accuracy	Poor System Calibration	Recalibrate IMU and sensor offsets/settings
	Inaccurate System	None
Laser Noise	Poor Laser Timing	None
	Poor Laser Reception	None
	Poor Laser Power	None
	Irregular Laser Shape	None

Operational measures taken to improve relative accuracy:

Low Flight Altitude: Terrain following was employed to maintain a constant above ground level (AGL). Laser horizontal errors are a function of flight altitude above ground (about 1/3000th AGL flight altitude).

Focus Laser Power at narrow beam footprint: A laser return must be received by the system above a power threshold to accurately record a measurement. The strength of the laser return (i.e., intensity) is a function of laser emission power, laser footprint, flight altitude and the reflectivity of the target. While surface reflectivity cannot be controlled, laser power can be increased and low flight altitudes can be maintained.

Reduced Scan Angle: Edge-of-scan data can become inaccurate. The scan angle was reduced to a maximum of ±14^o -29.26^o from nadir, creating a narrow swath width and greatly reducing laser shadows from trees and buildings.

Quality GPS: Flights took place during optimal GPS conditions (e.g., 6 or more satellites and PDOP [Position Dilution of Precision] less than 3.0). Before each flight, the PDOP was determined for the survey day. During all flight times, a dual frequency DGPS base station recording at 1 second epochs was utilized and a maximum baseline length between the aircraft and the control points was less than 13 nm at all times.

Ground Survey: Ground survey point accuracy (<1.5 cm RMSE) occurs during optimal PDOP ranges and targets a minimal baseline distance of 4 miles between GPS rover and base. Robust statistics are, in part, a function of sample size (n) and distribution. Ground survey points are distributed to the extent possible throughout multiple flight lines and across the survey area.

50% Side-Lap (100% Overlap): Overlapping areas are optimized for relative accuracy testing. Laser shadowing is minimized to help increase target acquisition from multiple scan angles. Ideally, with a 50% side-lap, the nadir portion of one flight line coincides with the swath edge portion of overlapping flight lines. A minimum of 50% side-lap with terrain-followed acquisition prevents data gaps.

Opposing Flight Lines: All overlapping flight lines have opposing directions. Pitch, roll and heading errors are amplified by a factor of two relative to the adjacent flight line(s), making misalignments easier to detect and resolve.