May 23, 2014

Hackensack Meadowlands, New Jersey

LiDAR Report of Survey Methods and Results

New Jersey Meadowlands Commission

Dom Elefante, GIS Program Administrator
New Jersey Meadowlands Commission
One De Korte Park Plaza
Lyndhurst, NJ 07071
PH: 202-423-5089

QSI Environmental
517 SW 2nd St., Suite 400
Corvallis, OR 97333
PH: 541-752-1204

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Cover Photo: A view of a water treatment plant along the Hackensack River. This image is composed of the highest hit surface model, draped with NAIP Imagery.

INTRODUCTION

This photo taken by QSI acquisition staff shows a view of the Hackensack Meadowlands site in New Jersey.

In February 2014, Quantum Spatial, Inc. (QSI) was contracted by the New Jersey Meadowlands Commission (NJMC) to collect Light Detection and Ranging (LiDAR) data in the spring of 2014 for the Hackensack Meadowlands site in New Jersey. Data were collected to aid the NJMC in assessing the topographic and geophysical properties of the study area to support habitat restoration and analysis of the Hackensack River and Meadowlands district.

This report accompanies the delivered LiDAR data and documents contract specifications, data acquisition procedures, processing methods, and analysis of the final dataset including a LiDAR FOCUS™ Accuracy report. Acquisition dates and acreage are shown in Table 1, a complete list of contracted deliverables provided to NJMC 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 Hackensack Meadowlands site

Project Site	Contracted Acres	Acquisition Dates	Data Type
Hackensack Meadowlands	33,665	04/09/2014 – 04/11/2014	LiDAR

Deliverable Products

Table 2: Products delivered to the NJMC for the Hackensack Meadowlands site

<table>
<tr><th colspan="2">Hackensack Meadowlands Products
Projection: New Jersey State Plane
Horizontal Datum: NAD83 (2011)
Vertical Datum: NAVD88 (GEOID12A)
Units: US Survey Feet</th></tr>
<tr><td>Points</td><td>LAS v 1.3
• Classified All Returns
• Raw Point Cloud</td></tr>
<tr><td>Rasters</td><td>2 Foot ESRI Grids and ERDAS Imagine Files
• Hydroflattened Bare Earth DEM
2 Foot GeoTiffs
• Normalized Intensity Images</td></tr>
<tr><td>Vectors</td><td>Shapefiles (*.shp)
• Site Boundary
• LiDAR Tile Index
• Ground Control (.shp & .dwg)
Geodatabase (*.gdb)
• Contours (1.0 ft) (.gdb & .dwg)
• Water’s Edge Breaklines</td></tr>
</table>

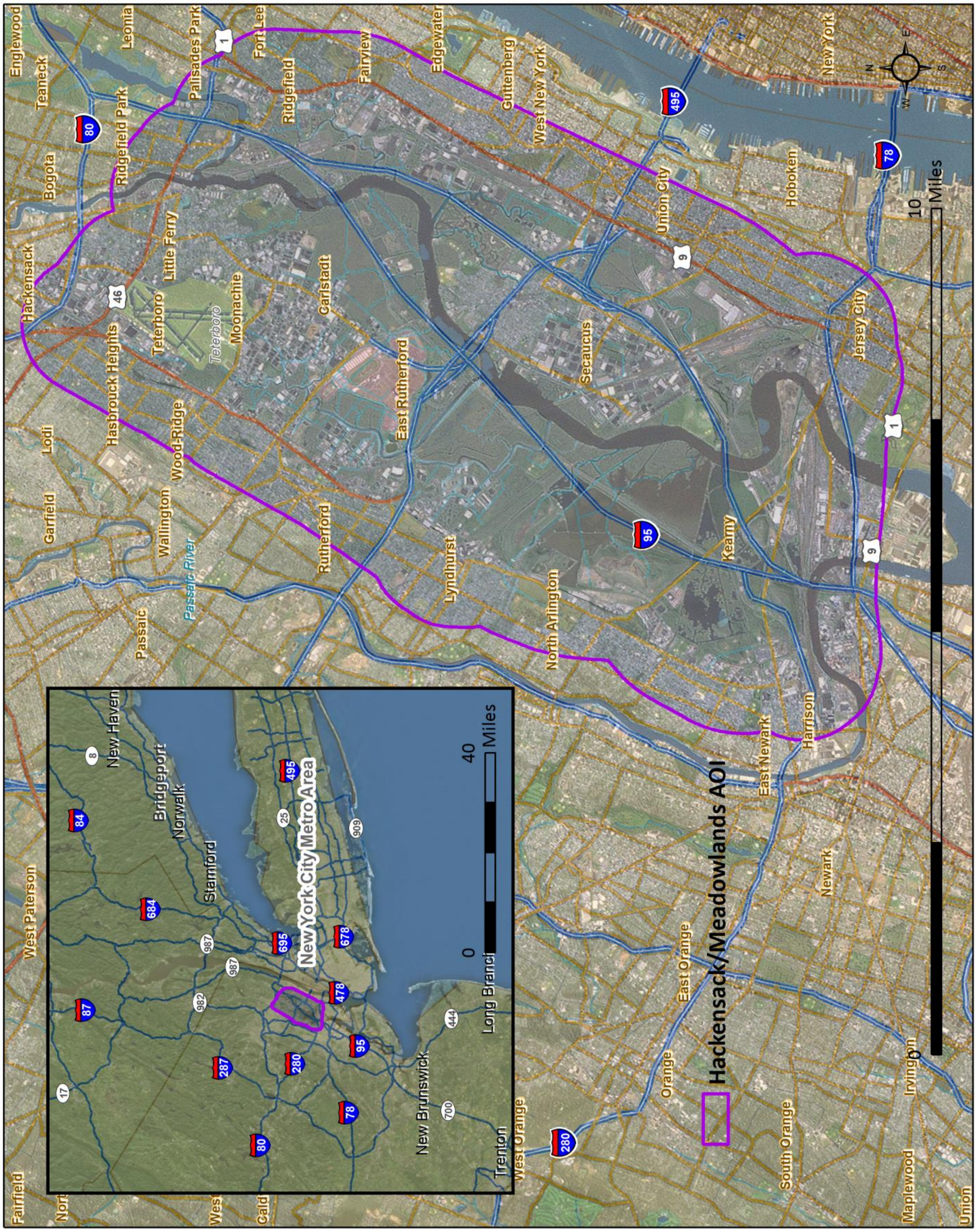


Figure 1: Location map of the Hackensack Meadowlands site in New Jersey

Survey Methods

QSI Cessna Caravan

Planning

In preparation for data collection, QSI reviewed the project area and developed a specialized flight plan to ensure complete coverage of the Hackensack Meadowlands LiDAR study area at the target point density of ≥8.0 points/m^2 (0.74 points/ft^2). Acquisition parameters including orientation relative to terrain, flight altitude, pulse rate, scan angle, and ground speed were adapted in order 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. Logistical considerations including private property access and potential air space restrictions were reviewed. Water levels and tidal conditions along the Hackensack River and surrounding Meadowlands were monitored to ensure airborne acquisition was completed during tidal periods below predicted Mean Sea Level (MSL) (Figure 2). 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.

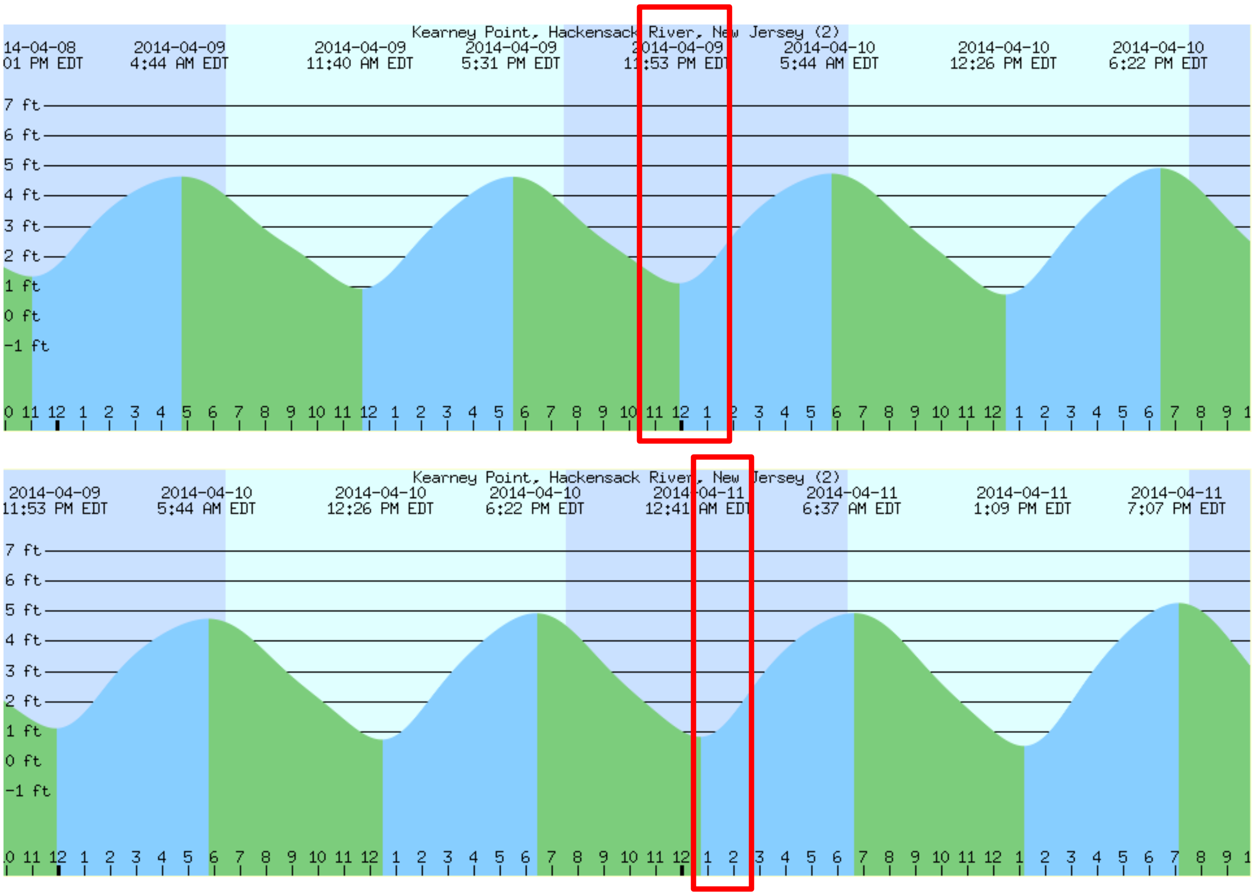


Figure 2: Tidal conditions at Kearney Point, Hackensack River, New Jersey (EDT) at the time of LiDAR acquisition between April 9, 2014 and April 11, 2014.

(http://tides.mobilegeographics.com/locations/3028.html?y=2014&m=4&d=9)

Airborne Survey

LiDAR

The Hackensack Meadowlands LiDAR survey was accomplished using a Leica ALS50 phase II system mounted in a Cessna Caravan. Table 3 summarizes the settings used to yield an average pulse density of ≥8.0 pulses/m^2 (0.74 pulses/ft^2) over the Hackensack Meadowlands project area. The Leica laser system records up to four range measurements (returns) per pulse. 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: LiDAR specifications and survey settings

LiDAR Survey Settings & Specifications	
Acquisition Dates	April 10 - 11, 2014
Aircraft Used	Cessna Caravan
Sensor	Leica ALS50 Phase II
Survey Altitude (AGL)	1500 m
Target Pulse Rate	105 kHz
Pulse Mode	Multiple Pulse in Air (MPiA)
Laser Pulse Diameter	34 cm
Field of View	24^o
GPS Baselines	≤13 nm
GPS PDOP	≤3.0
GPS Satellite Constellation	≥6
Maximum Returns	4
Intensity	8-bit
Resolution/Density	Average 8 pulses/m^2
Accuracy	$RMSE_Z$ ≤ 15 cm

Leica ALS50 LiDAR sensor

All areas were surveyed with an opposing flight line side-lap of ≥50% (≥100% 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 Control

NJMC Established Monument

Ground control surveys, including monumentation, and ground survey points (GSP), were conducted to support the airborne acquisition process. Ground control data were used to geospatially correct the aircraft positional coordinate data and to perform quality assurance checks on final LiDAR data.

Monumentation

The spatial configuration of ground survey monuments provided redundant control within 13 nautical miles of the mission areas for LiDAR flights. Monuments were also used for collection of ground survey points using real-time kinematic (RTK) and Fast Static (FS) survey techniques.

Monument locations were selected with consideration for satellite visibility, field crew safety, and optimal location for GSP coverage. QSI utilized two existing monuments and set one temporary survey pin for the Hackensack Meadowlands LiDAR project (Table 4, Figure 3). QSI's professional land surveyor, Nickolas R. Fusco (NJPLS #27711) oversaw and certified the occupation of all monuments.

Table 4: Monuments established for the Hackensack Meadowlands acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00

Monument ID	Latitude	Longitude	Ellipsoid (meters)
MCTR_07073-1	40° 48' 51.72120"	-74° 05' 36.06147"	-30.095
MCTR_07073-2	40° 48' 51.00248"	-74° 05' 35.17532"	-30.118
MDW_RTK_01	40° 44' 28.44444"	-74° 04' 32.14907"	-29.399

To correct the continuously recorded onboard measurements of the aircraft position, QSI concurrently conducted multiple static Global Navigation Satellite System (GNSS) ground surveys (1 Hz recording frequency) over each monument. During post-processing, the static GPS 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.

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

Monuments were established according to the national standard for geodetic control networks, as specified in the Federal Geographic Data Committee (FGDC) Geospatial Positioning Accuracy Standards for geodetic networks.[2] This standard provides guidelines for classification of monument quality at the 95% confidence interval as a basis for comparing the quality of one control network to another. The monument rating for this project is shown in Table 5.

Table 5: Federal Geographic Data Committee monument rating for network accuracy

Direction	Rating
1.96 * St Dev $_{NE}$:	0.020 m
1.96 * St Dev $_{z}$:	0.020 m

For the Hackensack Meadowlands LiDAR project, the monument coordinates contributed no more than 2.8 cm of positional error to the geolocation of the final ground survey points and LiDAR, with 95% confidence.

Ground Survey Points (GSP)

Ground survey points were collected using real time kinematic (RTK) survey techniques. A Trimble R7 base unit was positioned at a nearby monument to broadcast a kinematic correction to a roving Trimble R6 receiver. 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. When collecting RTK data, the rover records data while stationary for five seconds, then calculates the pseudorange position using at least three one-second epochs. Relative errors for the position must be less than 1.5 cm horizontal and 2.0 cm vertical in order to be accepted. See Table 6 for Trimble unit specifications.

GSP 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. GSP were collected within as many flightlines as possible, however the distribution of GSP depended on ground access constraints and monument locations and may not be equitably distributed throughout the study area (Figure 3).

Table 6: Trimble equipment identification

Receiver Model	Antenna	OPUS Antenna ID	Use
Trimble R6	Integrated GNSS Antenna R6	TRM_R6	Rover
Trimble R7 GNSS	Zephyr GNSS Geodetic Model 2	TRM57971.00	Static

[2] Federal Geographic Data Committee, Geospatial Positioning Accuracy Standards (FGDC-STD-007.2-1998). Part 2: Standards for Geodetic Networks, Table 2.1, page 2-3. http://www.fgdc.gov/standards/projects/FGDC-standards-projects/accuracy/part2/chapter2

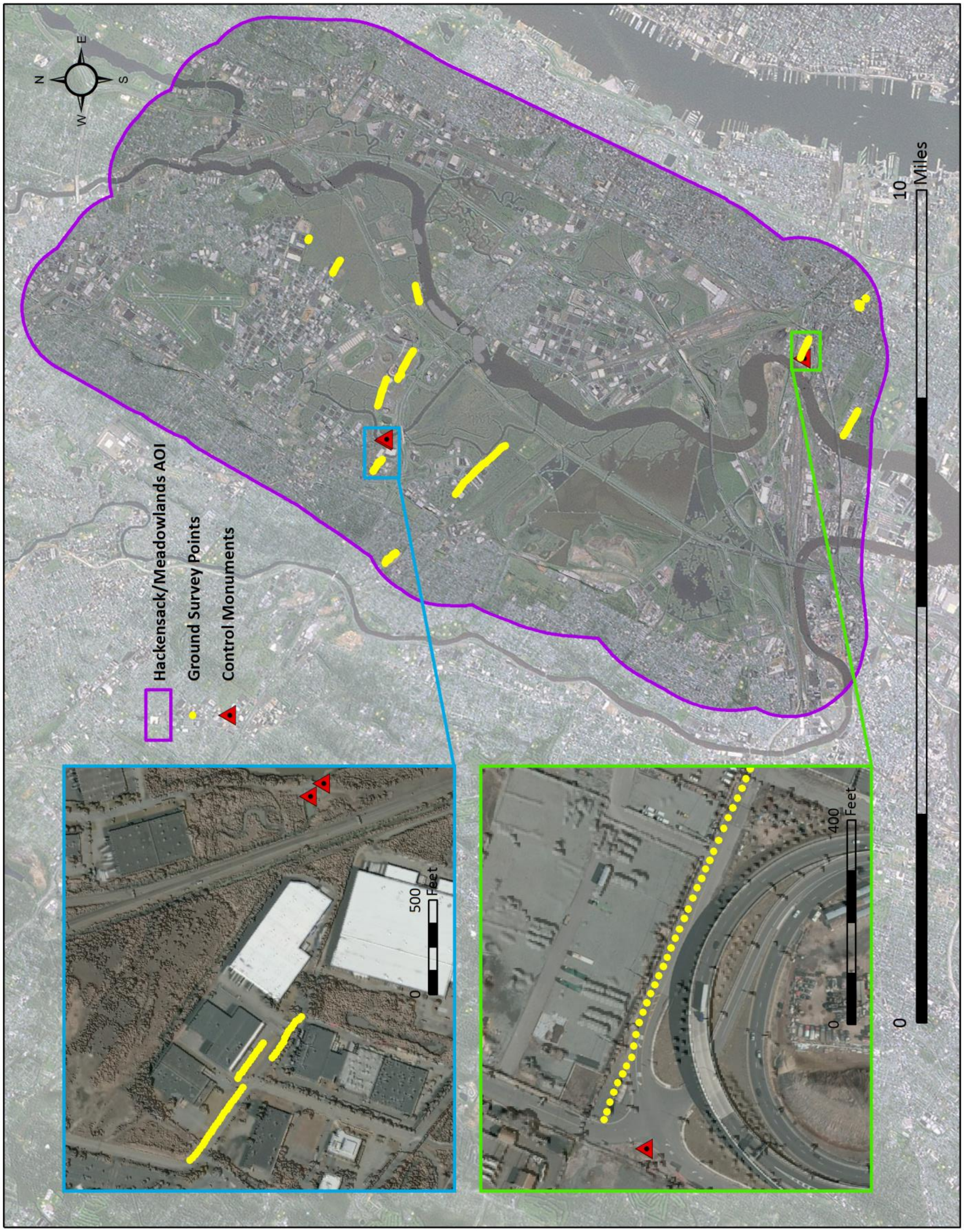
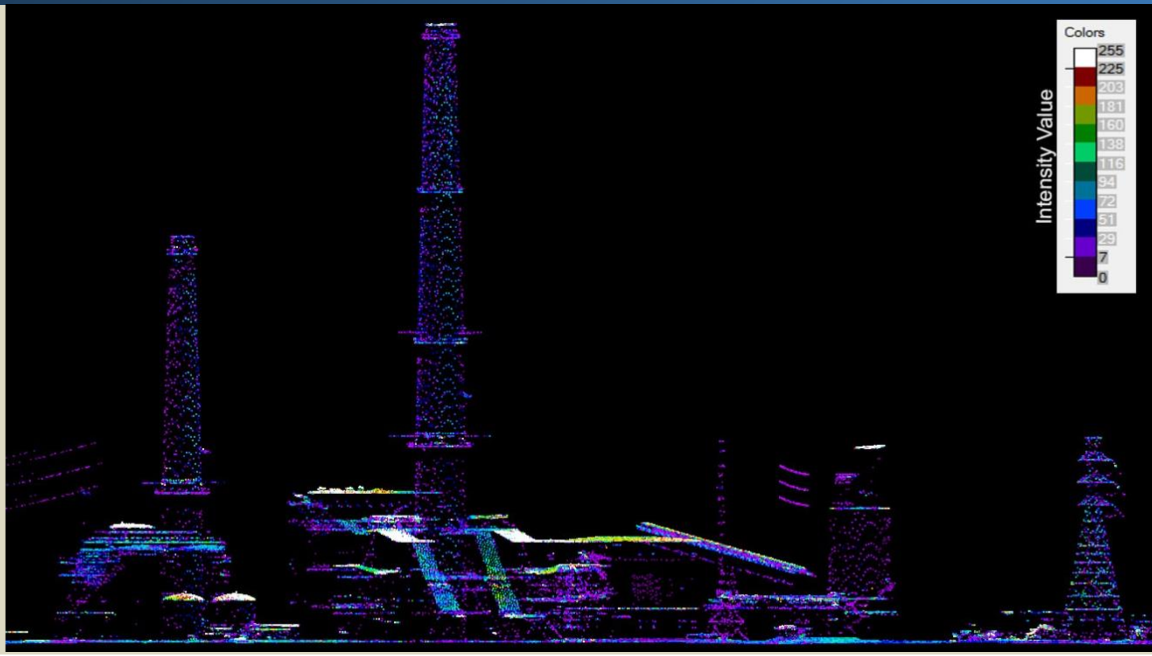


Figure 3: Ground Control map for the Hackensack Meadowlands Site

This cross section of a power plant along the Hackensack River shows the 3D LiDAR point cloud colored by intensity.



LiDAR Data

Upon completion of data acquisition, QSI 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 7). Processing methodologies were tailored for the landscape. Brief descriptions of these tasks are shown in Table 8.

Table 7: ASPRS LAS classification standards applied to the Hackensack Meadowlands dataset

Classification Number	Classification Name	Classification Description
1	Default/Unclassified	Laser returns that are not included in the ground class, composed of vegetation and man-made structures
2	Ground	Laser returns that are determined to be ground using automated and manual cleaning algorithms
9	Water	Laser returns that are determined to be water using automated and manual cleaning algorithms
10	Ignored Ground	Ground points proximate to water's edge breaklines; ignored for correct model creation

Table 8: 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.	IPAS TC v.3.1 Waypoint Inertial Explorer v.8.5
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. 1.3) format. Convert data to orthometric elevations by applying a geoid12a correction.	ALS Post Processing Software v.2.75
Import raw laser points into manageable blocks (less than 500 MB) to perform manual relative accuracy calibration and filter erroneous points. Classify ground points for individual flight lines.	TerraScan v.14
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.	TerraMatch v.14
Classify resulting data to ground and other client designated ASPRS classifications (Table 7). Assess statistical absolute accuracy via direct comparisons of ground classified points to ground control survey data.	TerraScan v.14 TerraModeler v.14
Generate bare earth models as triangulated surfaces. Generate highest hit models as a surface expression of all classified points. Export all surface models as ESRI GRIDs in EDRAS Imagine (.img) format at a 2.0 foot pixel resolution.	TerraScan v.14 ArcMap v. 10.1 TerraModeler v.14
Correct intensity values for variability and export intensity images as GeoTIFFs at a 2.0 foot pixel resolution.	TerraScan v.14 ArcMap v. 10.1 TerraModeler v.14

Intensity Normalization

Laser return intensity is a unitless measure of discrete return voltage, stored as an integer value from 0 to 255 (8-bit). Intensity values correspond to the reflectivity of the surface, which is a function of surface material composition. The magnitude of intensity values can vary across similar surfaces due to variability in receiver auto gain control (AGC), atmospherics, target range, and the angle of incidence. These components influence intensity at different rates and magnitudes, with AGC comprising the majority of influence. The result is line to line inconsistency and streaking in the images that can reduce the utility of these data for analysis.

Proprietary software was used to minimize variability caused by gain control, atmospheric transmissivity, range differences, and the angle of incidence to arrive at a normalized intensity value that approaches a true radiometric value for each discrete laser return. The result of the intensity normalization process is shown in Figure 4.

Non-Normalized Intensity ***Normalized Intensity***

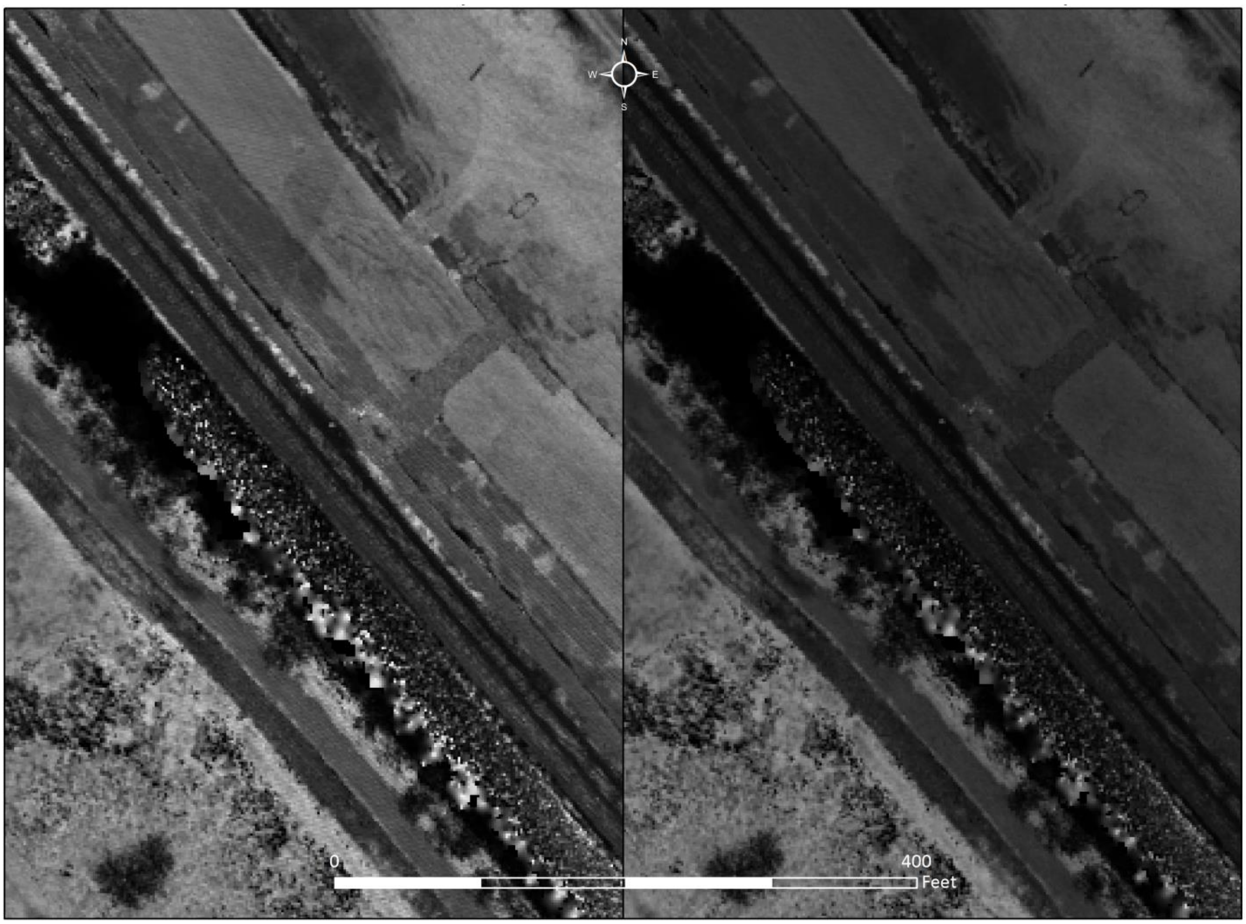


Figure 4: Comparison of normalized and non-normalized intensities

Feature Extraction

Hydro-flattening

The Hackensack River and other closed water bodies within the study area that met a minimum width of 100 ft were flattened to a consistent water level. The hydro-flattening process eliminated 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.

Hydro-flattening of closed water bodies was performed using a combination of automated and manual detection and adjustment techniques designed to identify water boundaries and levels. Water boundary polygons were developed using an algorithm which weights LiDAR-derived slopes, intensities, and return densities to detect the water edge. The water edges were then manually reviewed and edited as necessary.

Once polygons were developed, water elevations were obtained from the filtered LiDAR returns. Closed water bodies were assigned a consistent elevation for an entire polygon while the river was assigned consistent elevations on opposing banks and smoothed to ensure downstream flow through the entire river channel. The elevation of each closed water body was computed as 5 cm above the minimum elevation of filtered water surface cells within the water polygon. This approach ensures that all spurious returns off the water surface were excluded from lake level assessment. The initial ground classified points falling within water polygons were reclassified as water points to omit them from the final ground model and replaced with the flat water surface of the water boundary hydrolines.

Water boundary breaklines were then incorporated into the hydro-flattened 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 5).

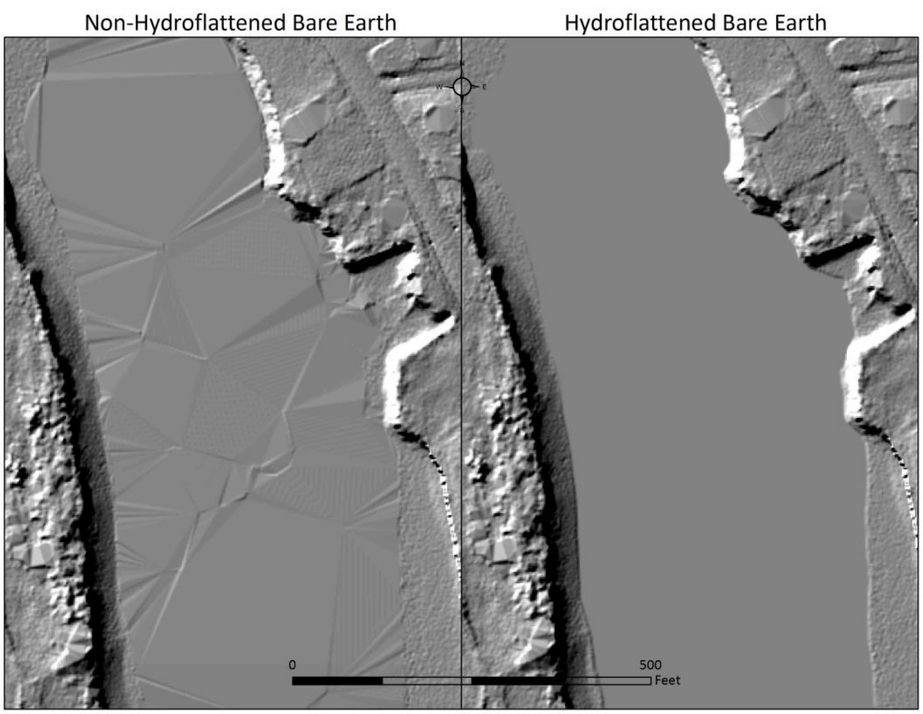


Figure 5: Example of hydro-flattening in the Hackensack Meadowlands LiDAR dataset

Contours

Contour generation from LiDAR point data required a thinning operation in order to reduce contour sinuosity. The thinning operation reduced point density where topographic change is minimal (i.e., flat surfaces) while preserving resolution where topographic change was present. These model key points were selected from the ground model every 20 feet with the spacing decreased in regions with high surface curvature (Z tolerance of 0.15 feet). Generation of model key points eliminated redundant detail in terrain representation, particularly in areas of low relief, and provided for a more manageable dataset. Contours were produced through TerraModeler by interpolating between the model key points at even elevation increments.

Elevation contour lines were then intersected with ground point density raster models and a confidence field was added to each contour line. Contours which crossed areas of high point density have high confidence levels, while contours which cross areas with low ground point density have low confidence levels. These areas with low ground point density were commonly beneath buildings and bridges, in locations with dense vegetation, over water, and in other areas where laser penetration to the ground surface was impeded (Figure 6).

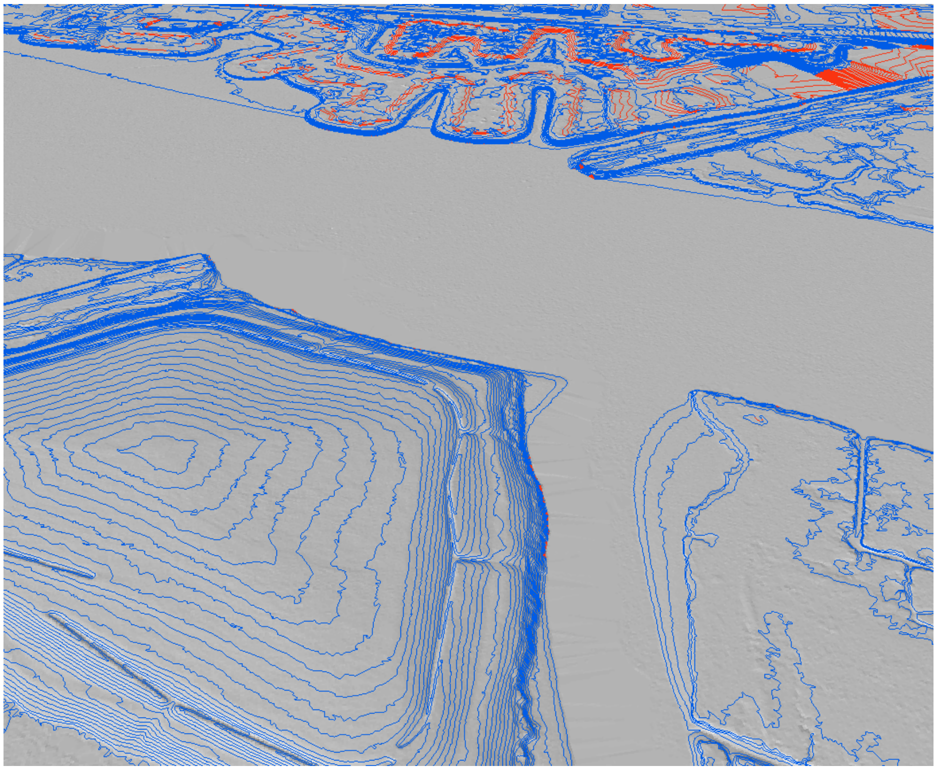
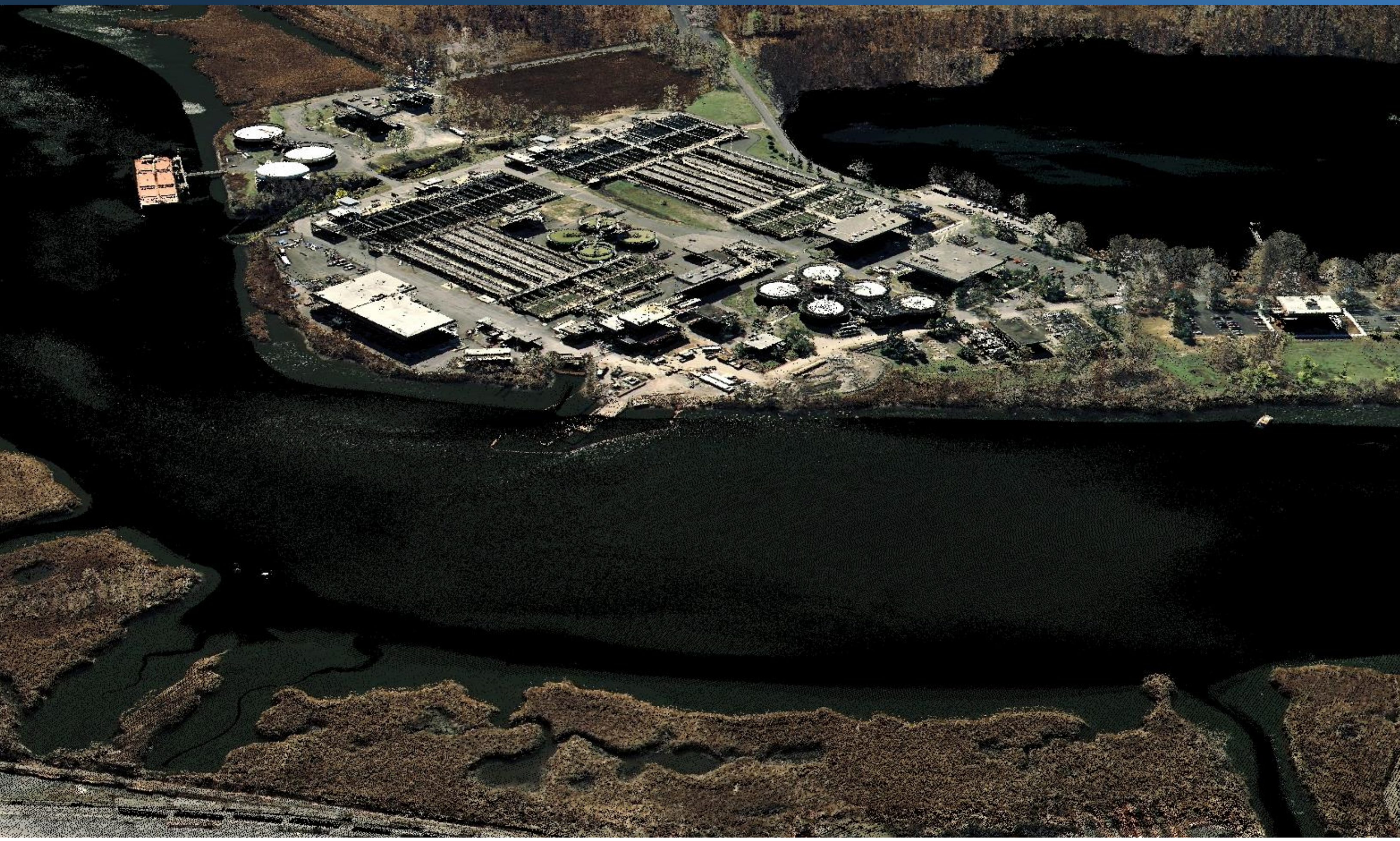


Figure 6: Contours draped over the Hackensack Meadowlands bare earth elevation model. Blue contours represent high confidence while the red contours represent low confidence.



LiDAR *FOCUS™*

FOCUS™ is a tool that was created by Photo Science, a Quantum Spatial company. FOCUS™ is an acronym for Final Observed and Calculated User Statistics and serves as an important reporting and quality control tool for LiDAR projects. This report provides a comprehensive evaluation of the Hackensack Meadowlands LiDAR derived elevation products.

After deliverable LAS and associated files are completed, FOCUS™ tools were run on the final LiDAR dataset and derived products to ensure delivery of a quality product. The results of these final tests are contained in the following section.

Summary

This summary includes LAS version information, point data format, units, projection, geoid model, datum, and any other pertinent project information. A quick “tile boundary” test was performed to verify that all points within a given tile fit within the exact boundary of the tile, and results are presented in terms of pass/fail. If the tile boundary test results in failure, an exception log is created that includes the tile name and the horizontal location and vertical position of all exceptions within that tile.

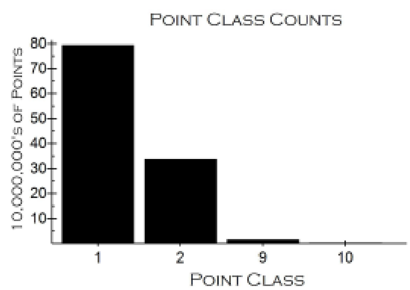
Detailed classification information of all LiDAR returns and a classification histogram can also be found in the summary, and serves to identify classification errors. Finally, a detailed look at the number of 1st, 2nd, 3rd, and 4th returns is provided, and results may aid in identifying sensor malfunction or unusually high or low return values during LiDAR acquisition.

Project Information

LAS Version	1.3	170 of 170 Tiles
Point Data Format	1	170 of 170 Tiles
Projection	New Jersey SP	170 of 170 Tiles
Horizontal Datum	NAD83	170 of 170 Tiles
Vertical Datum	NAVD88 survey feet	170 of 170 Tiles
Vertical Geoid	Unknown	170 of 170 Tiles
Minimum Ground	N 729,305.31 ft E 621,077.99 ft	Elev -10.66 ft
Maximum Ground	N 725,132.66 ft E 631,319.01 ft	Elev 287.11 ft
Planned NPS	0.4 meters	
Project Area	50.28 sq mi	
Tile Size	2,905 ft x 3,811 ft	
Start Of Aquisition	5/22/2014 2:13:39 AM UTC	
End Of Aquisition	5/23/2014 6:28:29 AM UTC	
Tile Boundary Test	Pass	

Point Classification Analysis

Classification	Point Count	Density
Class - All	1,129,823,042	8.68 ppsm
Class 1 - Default	790,948,744	6.07 ppsm
Class 2 - Ground	337,137,665	2.59 ppsm
Class 9 - Water	735,761	0.01 ppsm
Class 10 - Ignored Ground	1,000,872	0.01 ppsm



Point Return Statistics

Return 1 Points	1,072,727,355
Return 2 Points	53,267,530
Return 3 Points	3,828,088
Return 4 Points	69

Figure 7: FOCUS™ summary of results for the Hackensack Meadowlands LiDAR project in New Jersey

First Return Density Analysis

The ideal LiDAR acquisition would result in a perfectly uniform and square grid of laser returns that are evenly distributed throughout the project area with equal along- and cross-track dimensions. However, this “ideal” condition cannot be achieved due to environmental factors such as wind turbulence, elevation change, and surface reflectivity. In most cases, the simplest way to report the nominal point density is to calculate the total number of first returns as a percentage of points within the entire project area. Rather than using this simplistic approach, FOCUS™ tools uses a combination of three grids to better analyze the density of first return points, and to perform tests analogous to the spatial distribution and void tests as defined by the U.S. Geological Survey (USGS) LiDAR Base Specification Version 1.0[3].

The first FOCUS™ grid analysis applies a 1x1 meter grid to the project area, and views each square meter grid cell to count the number of first returns. Next, a histogram of the results is developed to determine the average (nominal) and standard deviation of first return densities for the entire project area. The test is then completed again using a grid of cells equal to the Nominal Point Spacing (NPS) x2, as well as a grid of cells equal to the NPS x4. The NPSx2 density analysis is the basis of a clustering, or spatial distribution test, while the NPS x4 density analysis serves as the basis of a void test in accordance with USGS LiDAR specifications.

Figure 8 illustrates this point. It should be apparent that the flight direction is in a northeast-southwest direction. In Acquisition A, the along- and cross-track point spacing is fairly consistent, indicating an effective flight plan. In Acquisition B, the cross track point spacing is much tighter (nominally about a 4 to 1 ratio) than the along-track spacing, which would be undesirable for most LiDAR projects. Note that the nominal point density is exactly the same for both at 2.9 ppsm. The standard deviation, however, is considerably higher for Acquisition B.

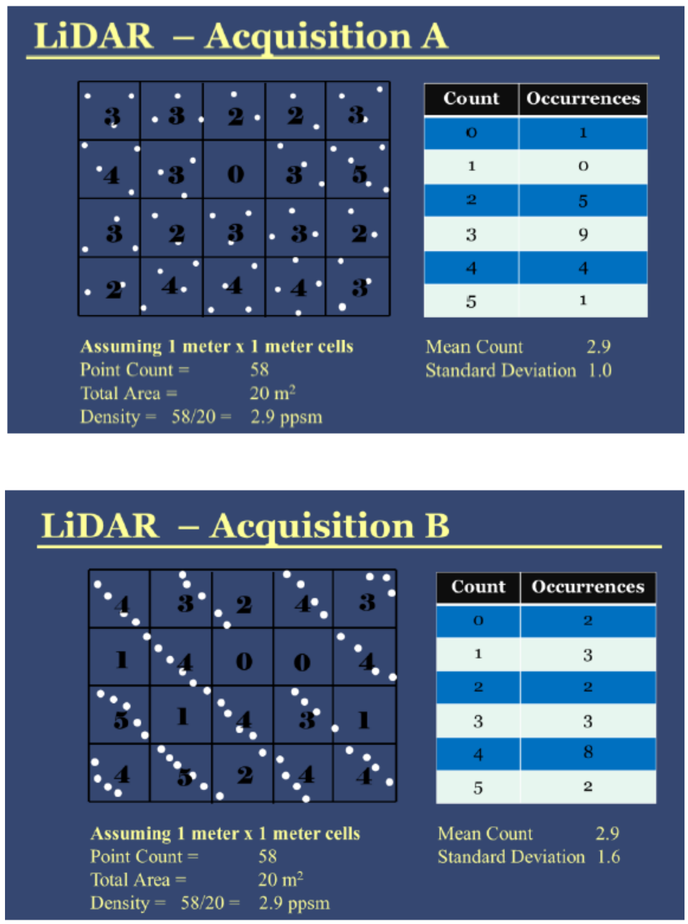


Figure 8: A comparison of sample grid analyses using the traditional approach as compared to the FOCUS™ approach

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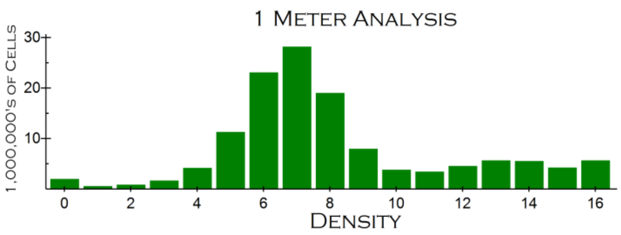
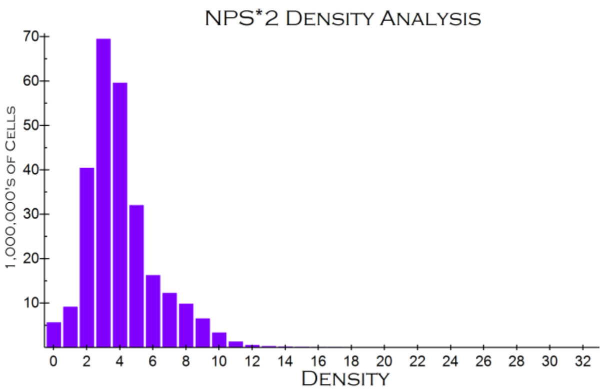
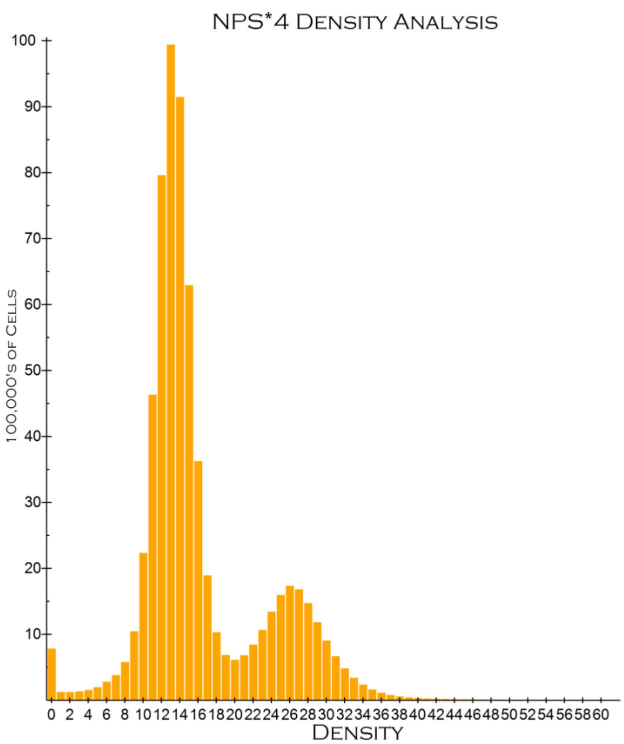
[3] Heidemann, Hans Karl, 2012, LiDAR base specification version 1.0, U.S. Geological Survey Techniques and Methods, book 11, chap. B4, 63p.



1 Meter Cell			
Average	8.22	Standard Dev.	3.59
Return Count	# of Cells	Return Count	# of Cells
0	1,897,197	9	7,873,037
1	482,889	10	3,716,475
2	763,128	11	3,335,356
3	1,570,626	12	4,458,561
4	4,078,905	13	5,555,543
5	11,205,958	14	5,438,183
6	22,988,324	15	4,142,541
7	28,091,111	16+	5,556,496
8	18,921,940		



0.7 Meter Cell (NPS*2)			
Average	4.03	Standard Dev.	2.12
Return Count	# of Cells	Return Count	# of Cells
0	5,552,237	17	16,713
1	9,057,166	18	9,478
2	40,328,205	19	5,673
3	69,389,591	20	3,458
4	59,494,002	21	2,381
5	31,938,277	22	1,470
6	16,171,735	23	1,081
7	12,159,998	24	814
8	9,735,005	25	622
9	6,430,284	26	517
10	3,248,184	27	379
11	1,220,042	28	322
12	435,954	29	240
13	185,550	30	235
14	95,286	31	185
15	52,286	32+	1,223
16	29,125		



1.4 Meter Cell (NPS*4)			
Average	16.11	Standard Dev.	6.65
Return Count	# of Cells	Return Count	# of Cells
0	775,905	31	660,587
1	116,860	32	475,548
2	115,681	33	333,360
3	125,461	34	229,317
4	147,528	35	155,958
5	189,390	36	105,099
6	271,922	37	71,496
7	372,494	38	49,383
8	570,836	39	34,711
9	1,037,676	40	25,214
10	2,226,107	41	18,599
11	4,625,651	42	14,153
12	7,952,309	43	10,911
13	9,934,045	44	8,503
14	9,139,616	45	6,570
15	6,284,430	46	5,196
16	3,617,898	47	3,987
17	1,884,683	48	3,133
18	1,023,786	49	2,413
19	679,239	50	1,922
20	605,176	51	1,525
21	675,029	52	1,177
22	834,575	53	907
23	1,060,679	54	767
24	1,336,146	55	629
25	1,589,449	56	495
26	1,727,478	57	426
27	1,673,307	58	386
28	1,464,726	59	293
29	1,176,021	60+	2,459
30	897,914		

Figure 9: FOCUS™ first return density analysis for the Hackensack Meadowlands LiDAR Project

Shaded Relief Map

The shaded relief map was generated from each deliverable tile, and provides an overall view of the project area along with the terrain captured by LiDAR acquisition. The shaded relief was draped over the tile index and project boundary. This graphic allows for a quick visual check for missing or corrupt tiles (they will not be shaded, therefore, they will appear as void), and can also illustrate large data gaps within individual tiles.

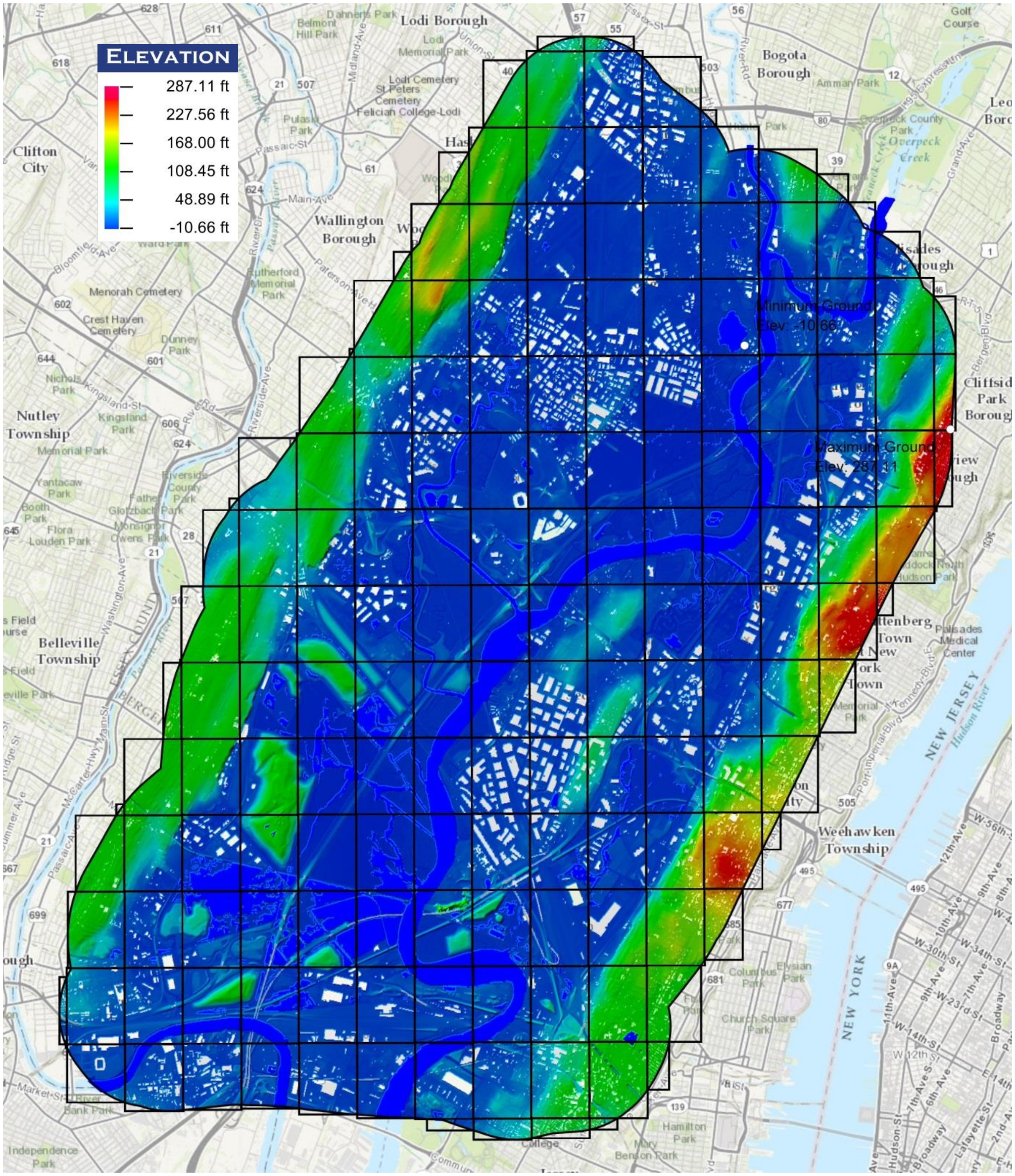


Figure 10: Hackensack Meadowlands shaded relief map

Minimum and Maximum Surface Elevations

The minimum surface elevation graphic depicts the minimum elevation within the ground classified points (class 2) for each deliverable tile, while the maximum surface elevation graphic depicts the maximum ground-classified elevation within each deliverable tile. In order to produce both graphics, each deliverable tile was subdivided into 50 rows and 50 columns; the minimum elevation within each sub-grid was rendered. Both graphics are helpful in determining unusually high or low points within the LiDAR dataset.

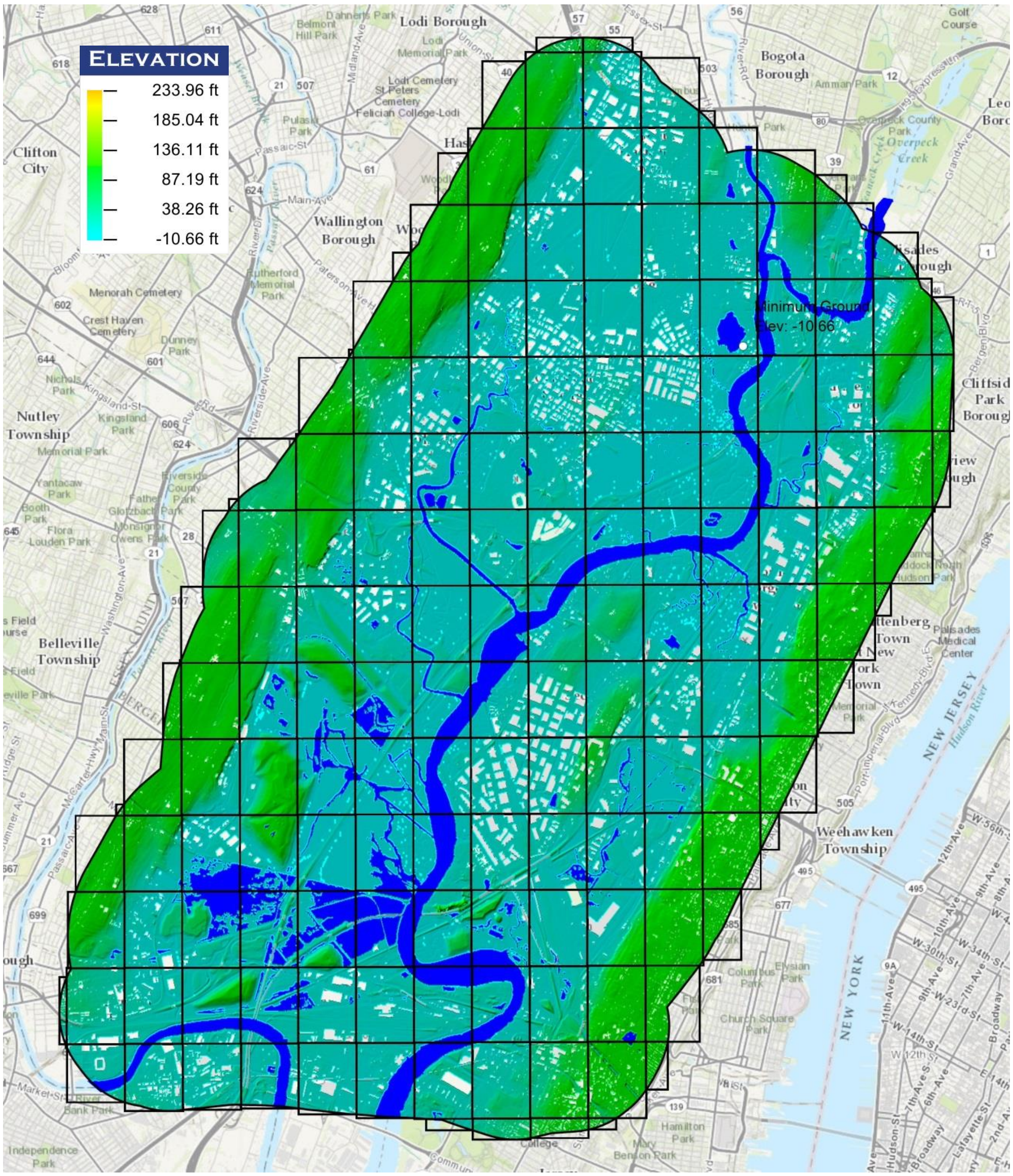


Figure 11: Minimum surface elevation map for the Hackensack Meadowlands project

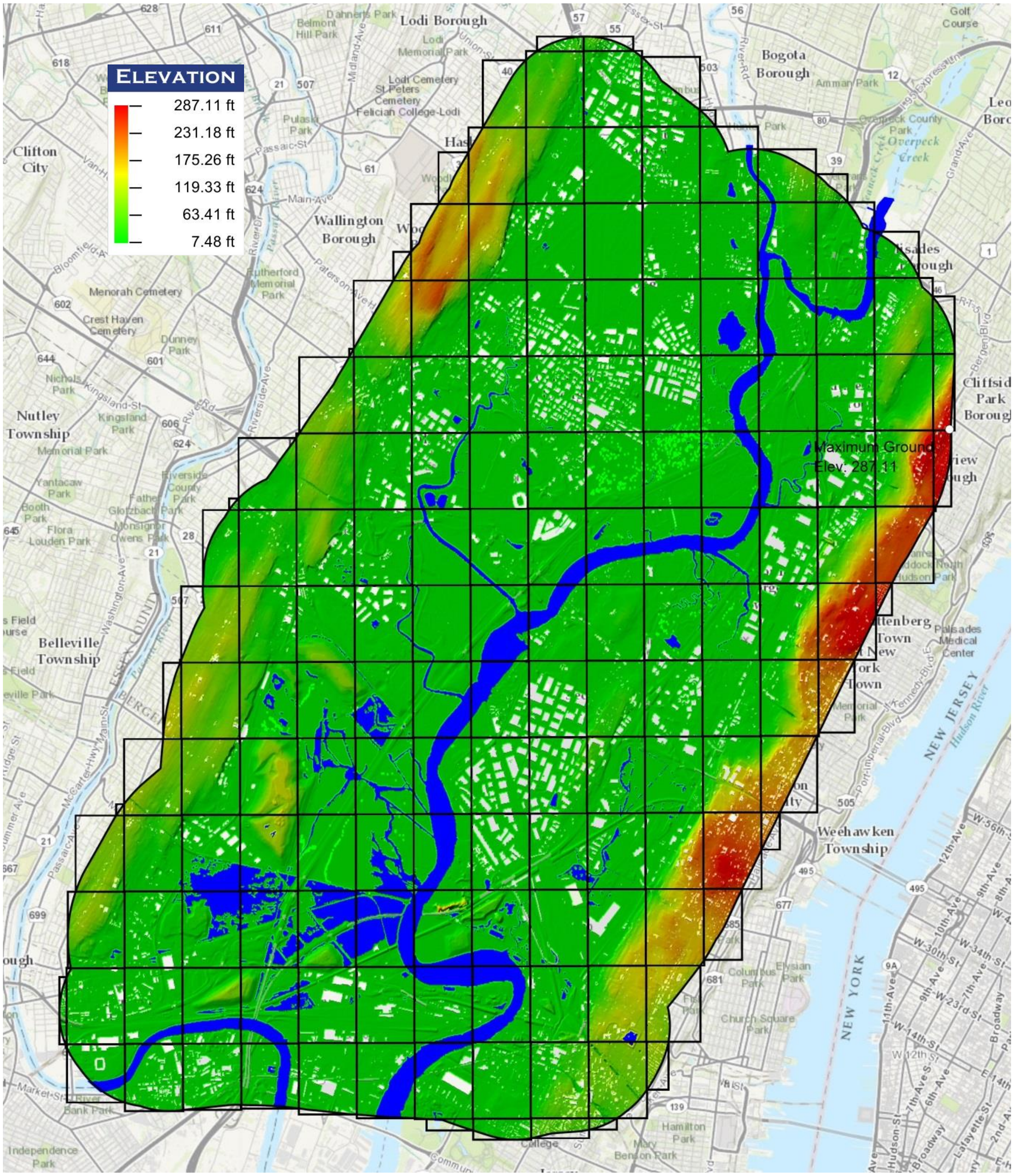


Figure 12: Maximum surface elevation map for the Hackensack Meadowlands project

Relative Terrain Change

This relative terrain change graphic represents the amount of elevation change within each 50x50 sub-gridded tile within the Hackensack Meadowlands project area. The difference in maximum and minimum ground elevations was determined and rendered within the maximum and minimum surface elevation graphics.

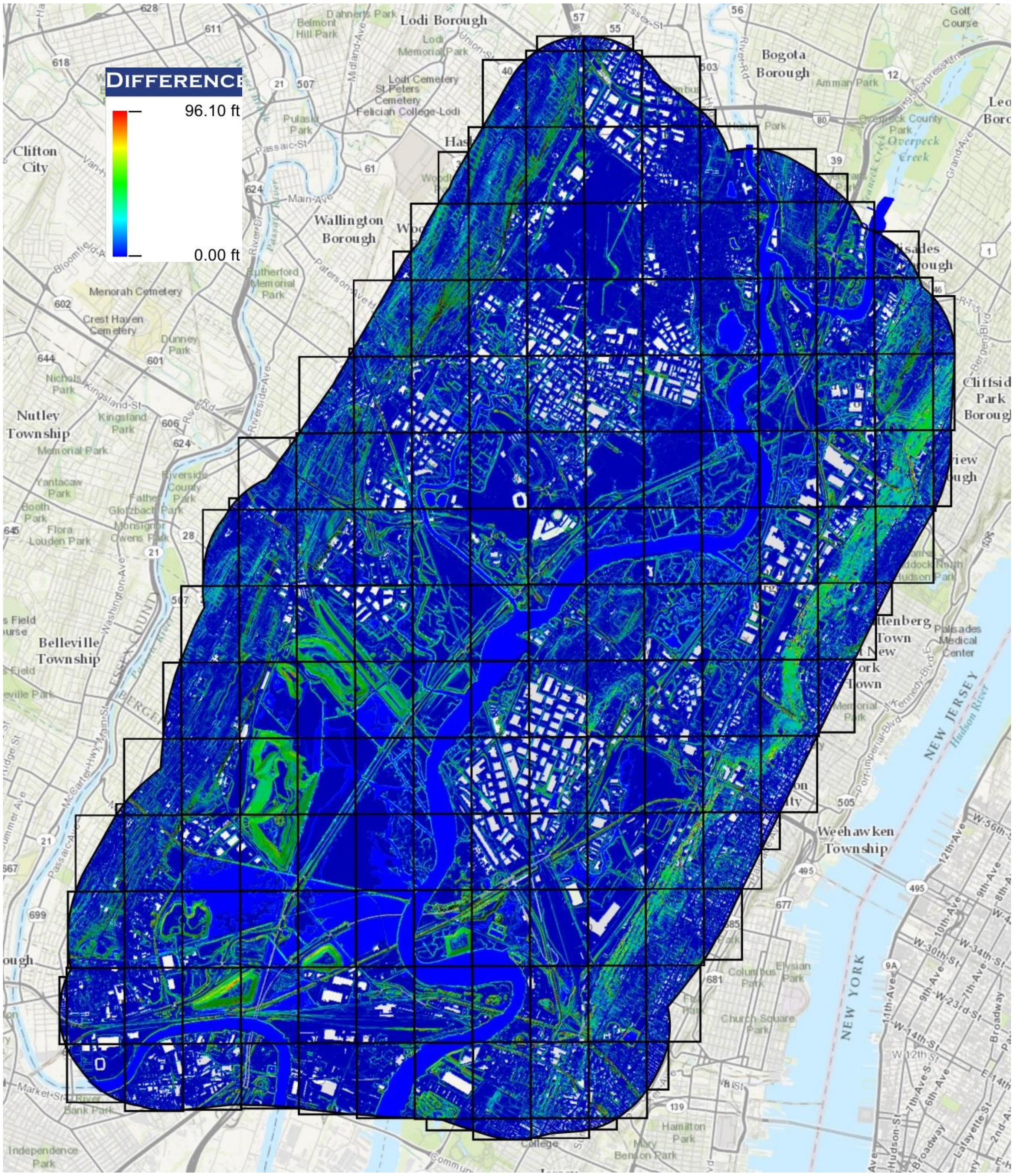


Figure 13: Relative terrain change map within the Hackensack Meadowlands site

Second, Third, and Fourth Return Locations

The following return graphics provide detailed information for the location of all second, third, and fourth returns within the Hackensack Meadowlands project area (Figure 15, Figure 16, and Figure 17). These graphics were derived from the relative density of returns within the 50x50 sub-grid of each tile. A count of the number of second, third, and fourth returns was derived within each cell, and then rendered to the entire project area. Cells with very low return densities appear transparent, while cells with higher return densities appear darker.

Note that the graphic for fourth returns must be a subset of the second and third return graphics because fourth (or last) returns are preceded by all other returns. Similar logic applies to the third return graphic related to the second return graphic. Third and fourth return location analysis may often indicate the lack or presence of relatively tall vegetation (Figure 14). This is because most current discrete-return LiDAR sensors have a minimum pulse discrimination distance ranging from approximately 0.75 to 3.0 meters. This means that the sensor cannot record a second return within the given discrimination range from the first return (as well as the third return from the second return, etc.). Therefore, in order to achieve fourth returns, the distance between the first and fourth return must be nominally 3 times that of the pulse discrimination distance, or more. For example, in the case of a sensor with a discrimination distance of 1.5 meters, the first return must be at least 4.5 meters (or about 15 feet) higher than the fourth.

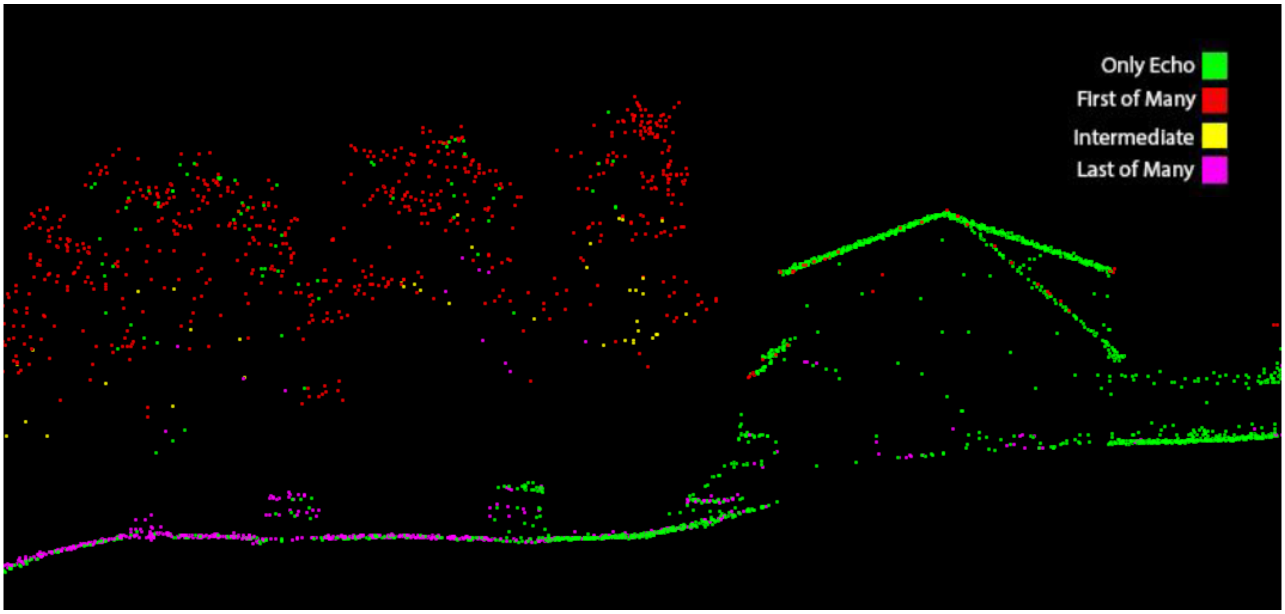


Figure 14: This 2 meter LiDAR cross section shows an example of the variation between first and last return points in the Hackensack Meadowlands site.

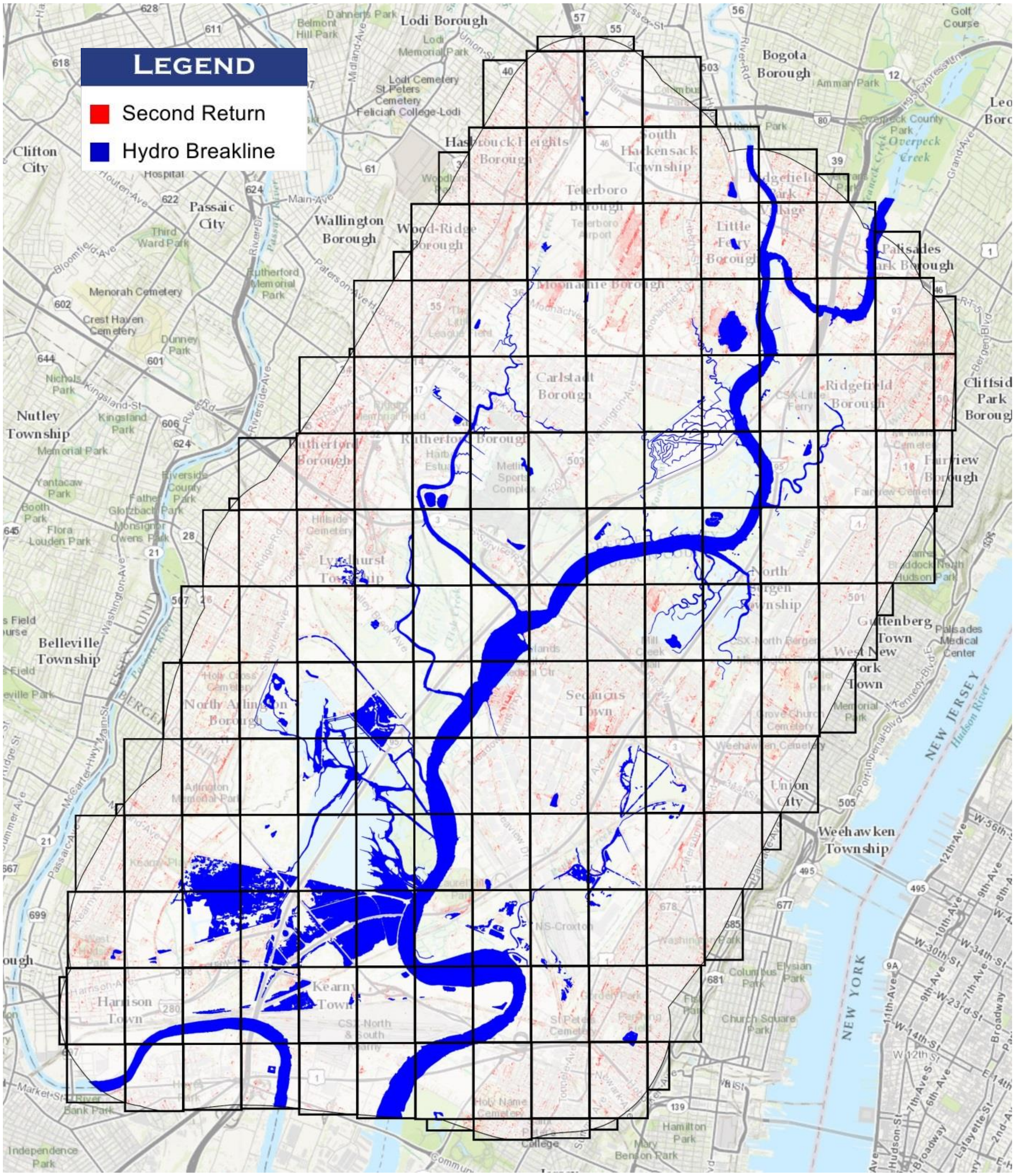


Figure 15: Second return locations within the Hackensack Meadowlands survey site

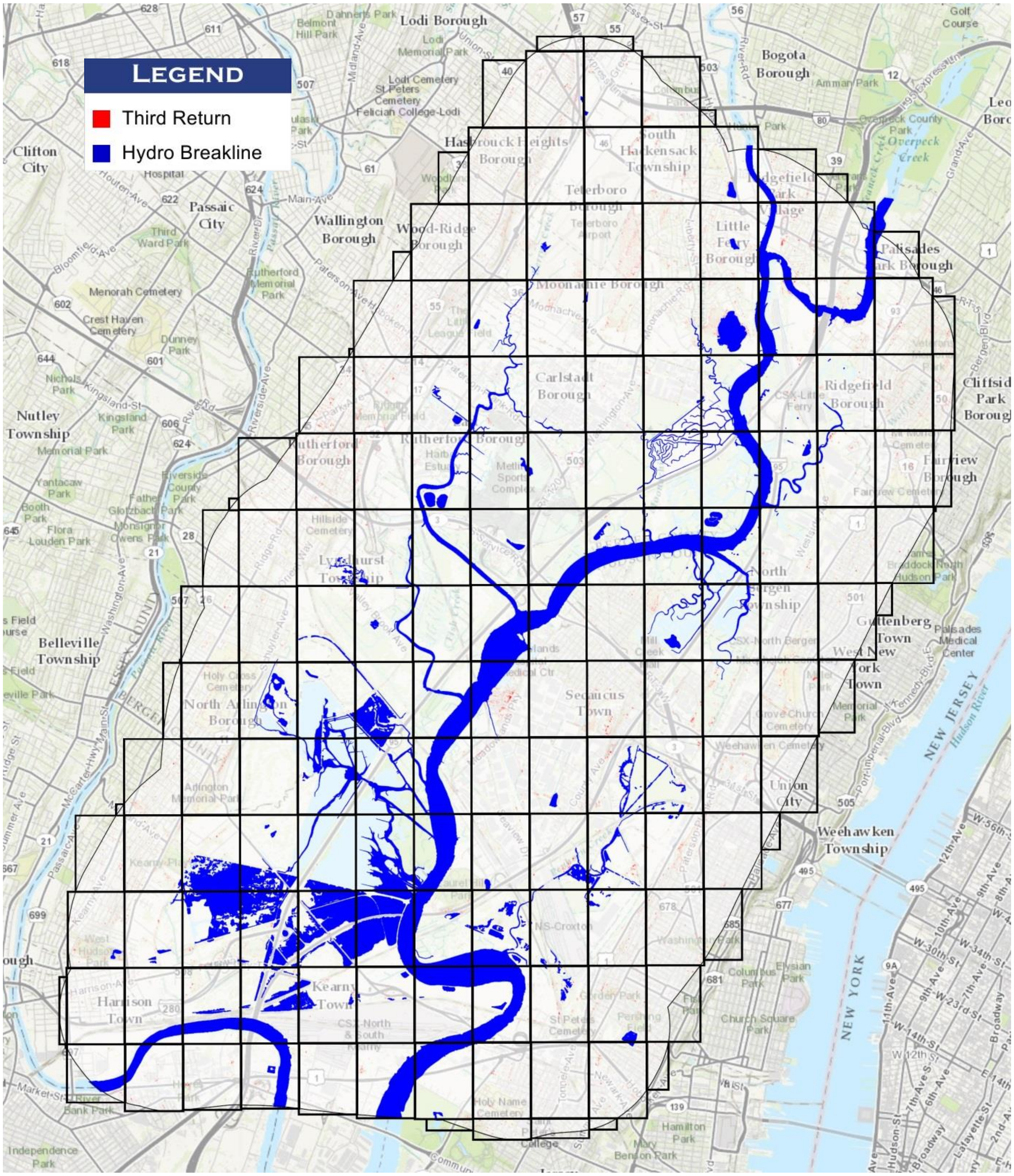


Figure 16: Third return locations within the Hackensack Meadowlands survey site

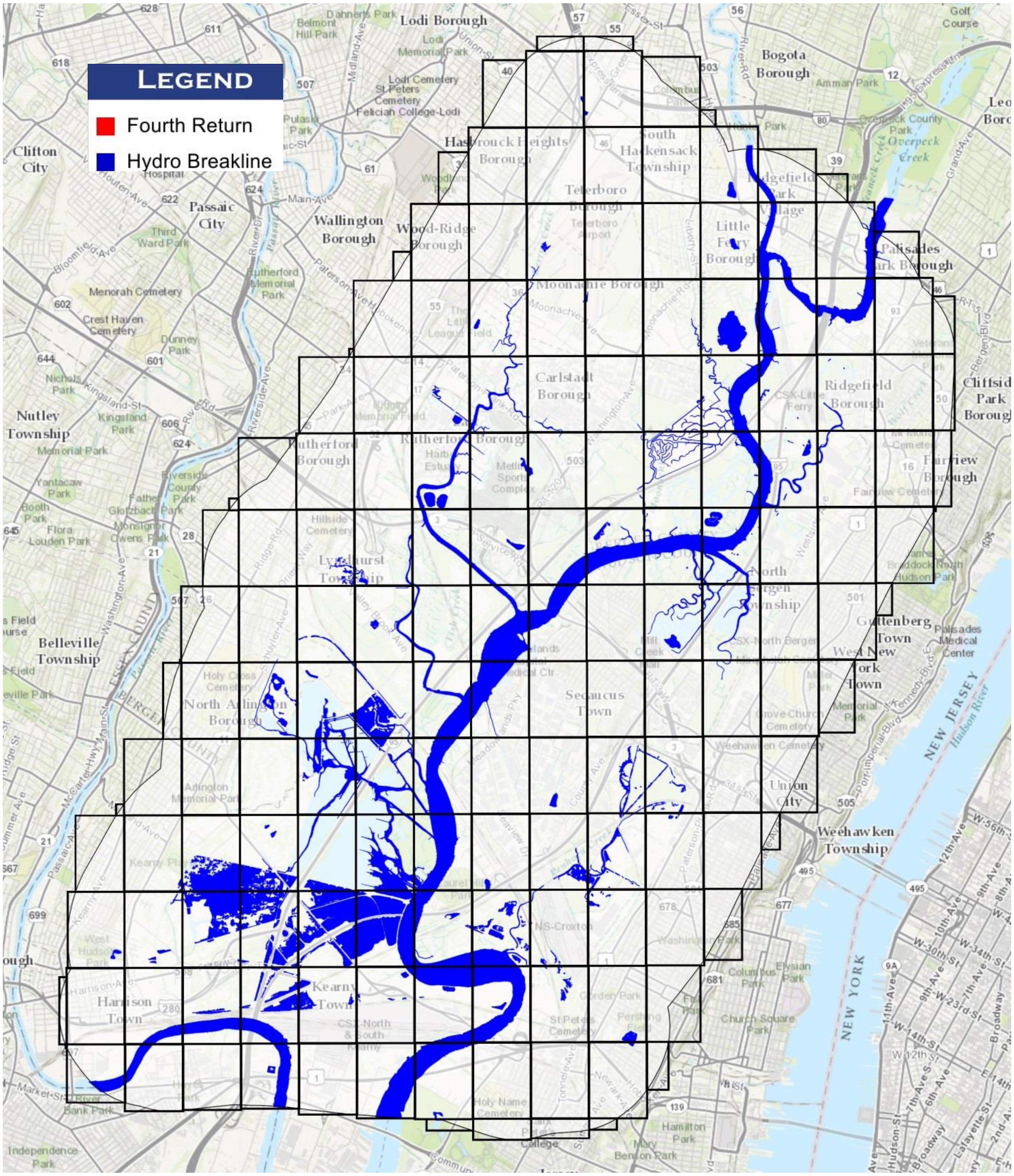


Figure 17: Fourth return locations within the Hackensack Meadowlands survey site

One can see that for the Hackensack Meadowlands survey site, fewer third and fourth returns were achieved. This is because first returns typically reflect off the highest feature on the landscape within the footprint of the pulse. In an urban area like New Jersey, it is expected to see a greater amount of first and second returns, with fewer third and fourth returns due to the nature of the terrain.

First Return Point Density Map

This graphic depicts the point density of first returns for each tile within the Hackensack Meadowlands survey site. 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. Pulse density distribution varied within the study area due to laser scan pattern and flight conditions. Additionally, 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 return density was determined by dividing the total number of returns within a tile using classes 1, 2, 9, and 10, by the total area of the tile. This value is expressed in units of points per square meter (ppsm) regardless of the units selected (feet or meters) for the project. If the project boundary splits a tile, the calculation takes place only within the project boundary. Translucent colors were used in this graphic so that the project map is displayed behind the rendering, allowing the viewer to see any natural features that may cause lower first return densities for any given tile.

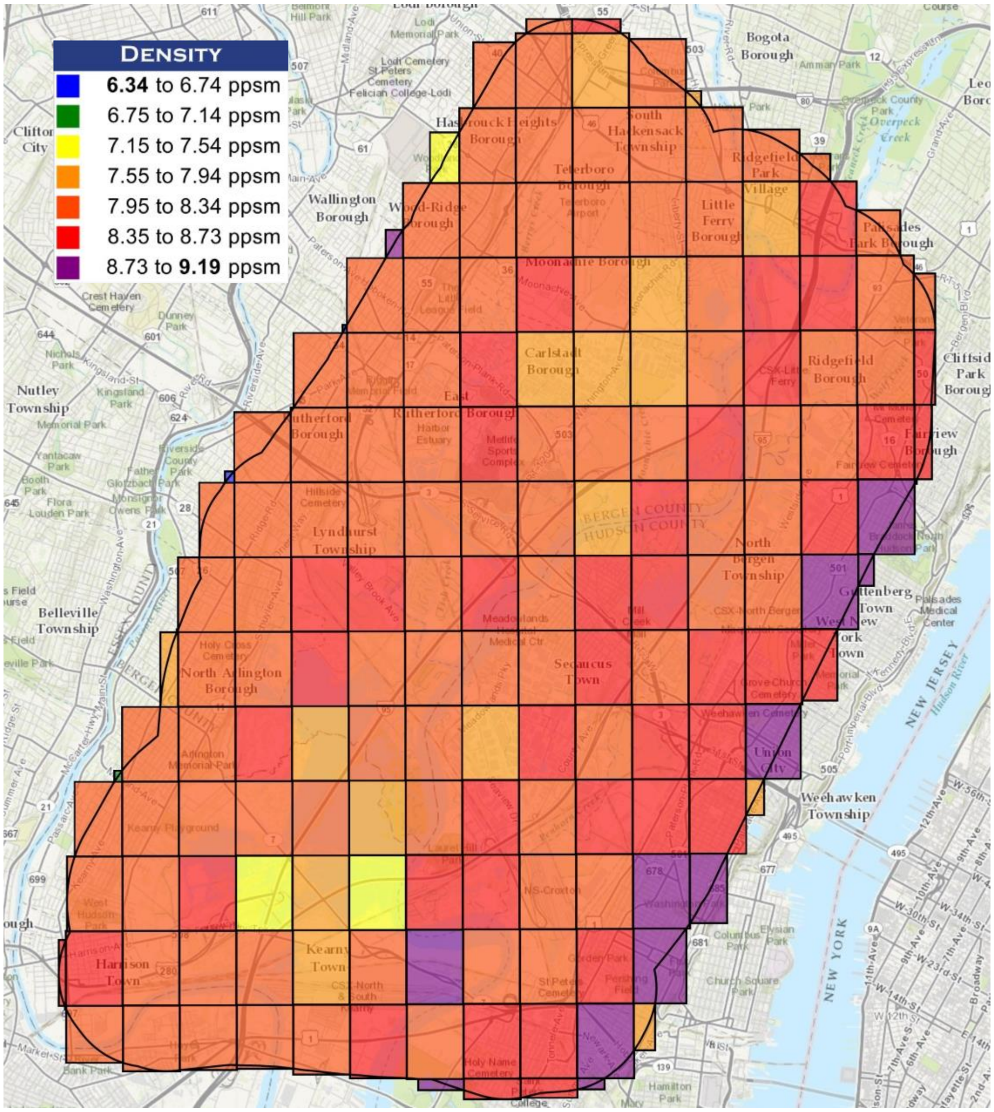


Figure 18: First return point density map of the Hackensack Meadowlands project

First Return Spatial Distribution Test

The clustering and void graphics provide results of the spatial distribution test, (or clustering test) as well as void tests, as required by the USGS LiDAR base specification. The LiDAR first returns were overlaid with a uniform grid size that has sides of Nominal Point Spacing (NPS)x2 and NPSx4. For example, a project with a NPS of 0.7 meters would result in an NPSx2 grid size of 1.4 meters on each side. Each grid cell within the project boundary was examined to determine if there are any returns that lie within it; if at least one return fell within a cell it was identified as "populated". If no returns fell within a given cell, it was identified as "void" of returns. Any cell that either touches a hydro breakline, or falls entirely within a hydro breakline was removed from the test.

For spatial distribution testing, the USGS specification requires that at least 90% of the tested cells contain at least one return. The results of this test are presented graphically by tile with the percentage of "filled" cells rendered for each tile. The legend provides the color scheme. The results will be negatively skewed by projects that either do not contain hydro breaklines, or projects with a considerable number of small water bodies that fall below the threshold for breakline collection (e.g., small ponds or narrow streams).

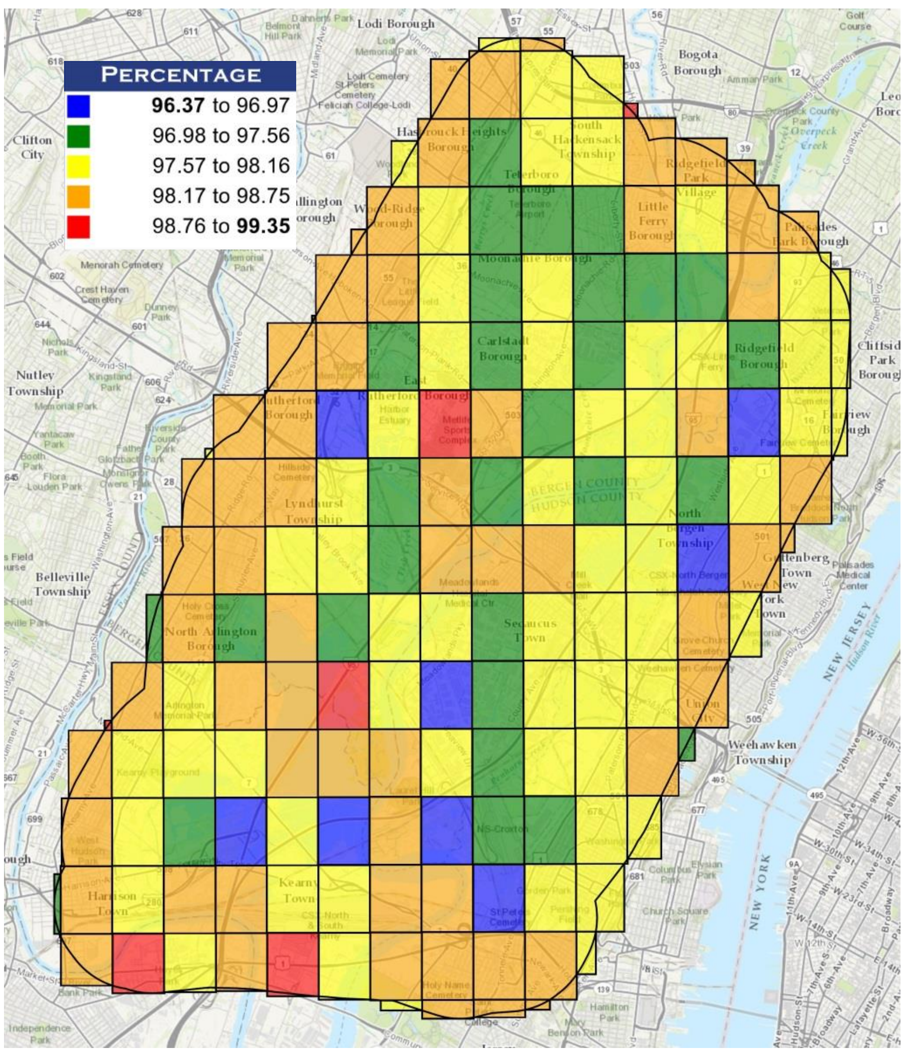


Figure 19: First return spatial distribution map

First Return Void Testing at NPSx2 and NPSx4

In addition to spatial distribution tests, First Return Void graphics at NPSx2 and NPSx4 are presented. For void testing, the USGS specification defines data voids within a single swath as unacceptable, except when caused by water bodies, areas of low near-infrared reflectivity, or where filled in by another swath. USGS specification version 1.0 requires that 90% of all cells of dimension NPSx2 that are evaluated within the project contain at least one LiDAR return. It is extremely rare for this void test to result in no voids within a dataset, but the location of the voids are almost always found in small streams or ponds that are less than the collection requirements for non-reflective surfaces.

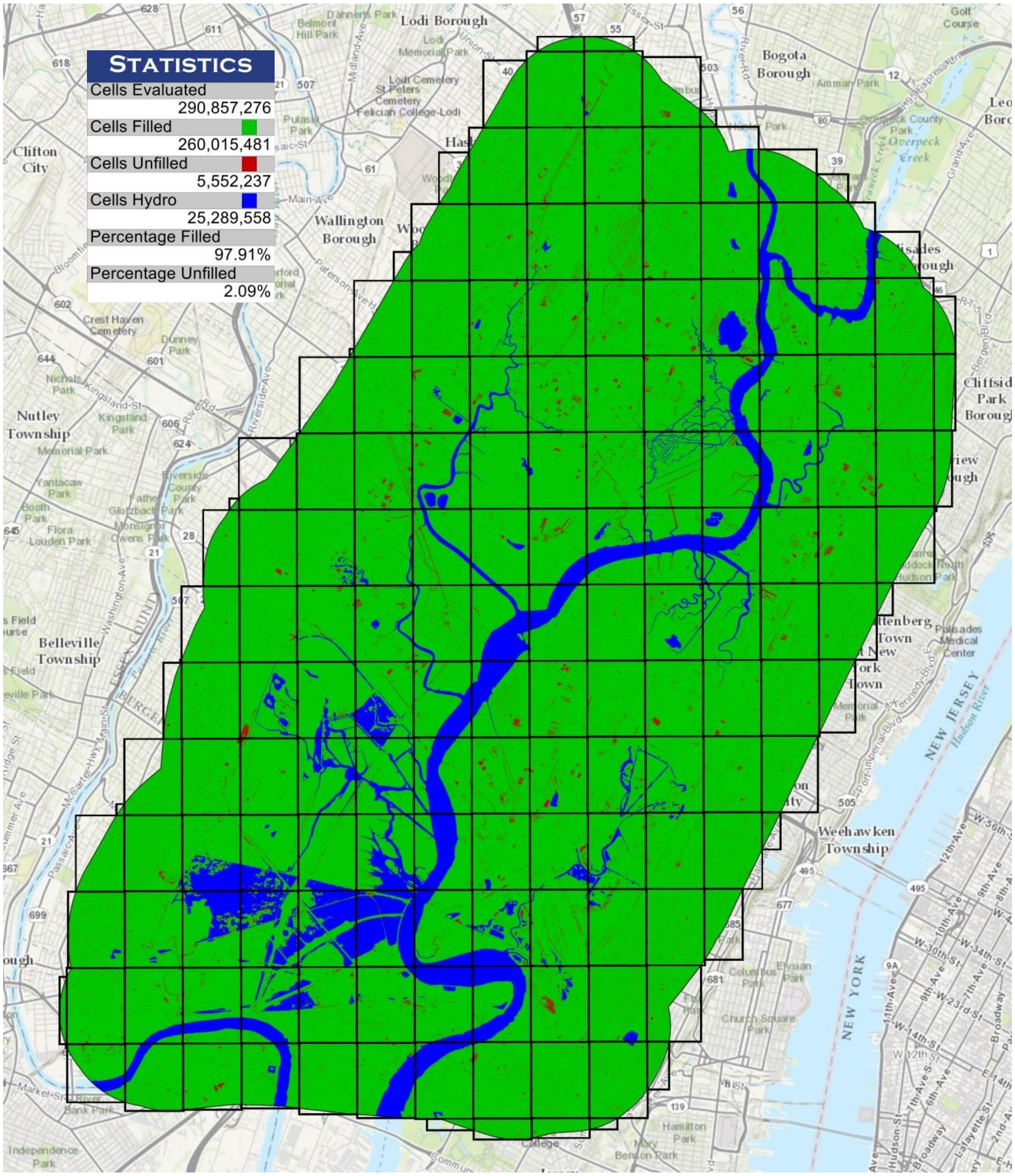


Figure 20: First return voids with grid cell size NPSx2

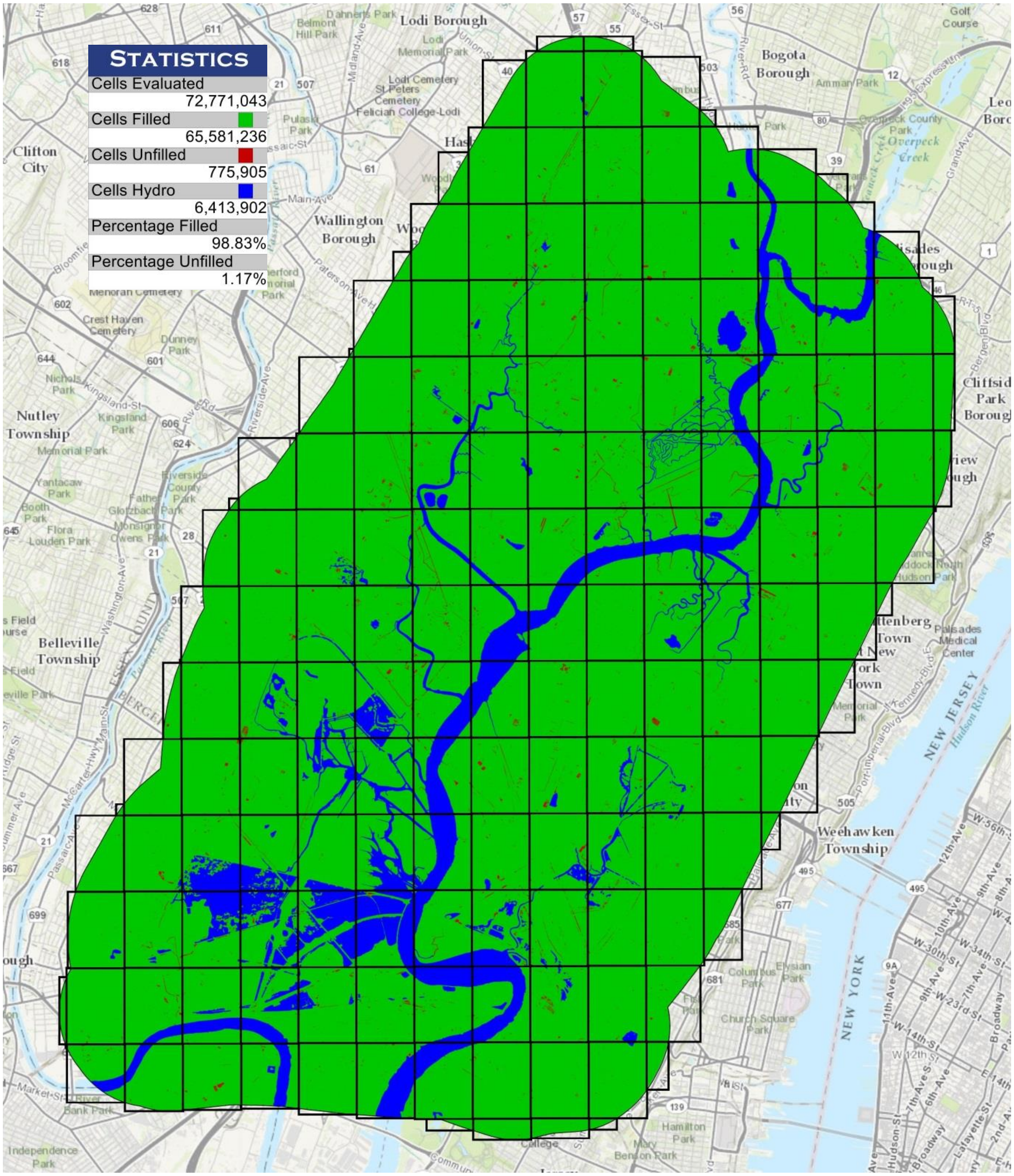


Figure 21: First return voids with grid cell size NPSx4

Bare Earth Density

The bare earth density graphic depicts the ground classified, i.e., bare earth, point density for each delivered tile. Ground point density is determined by dividing the total number of bare earth ground returns per tile by the total area of the tile, and is expressed in ppsm. Terrain character, land cover, and ground surface reflectivity all influenced the density of ground surface returns. In densely urban areas, less ground is exposed, resulting in lower ground density.

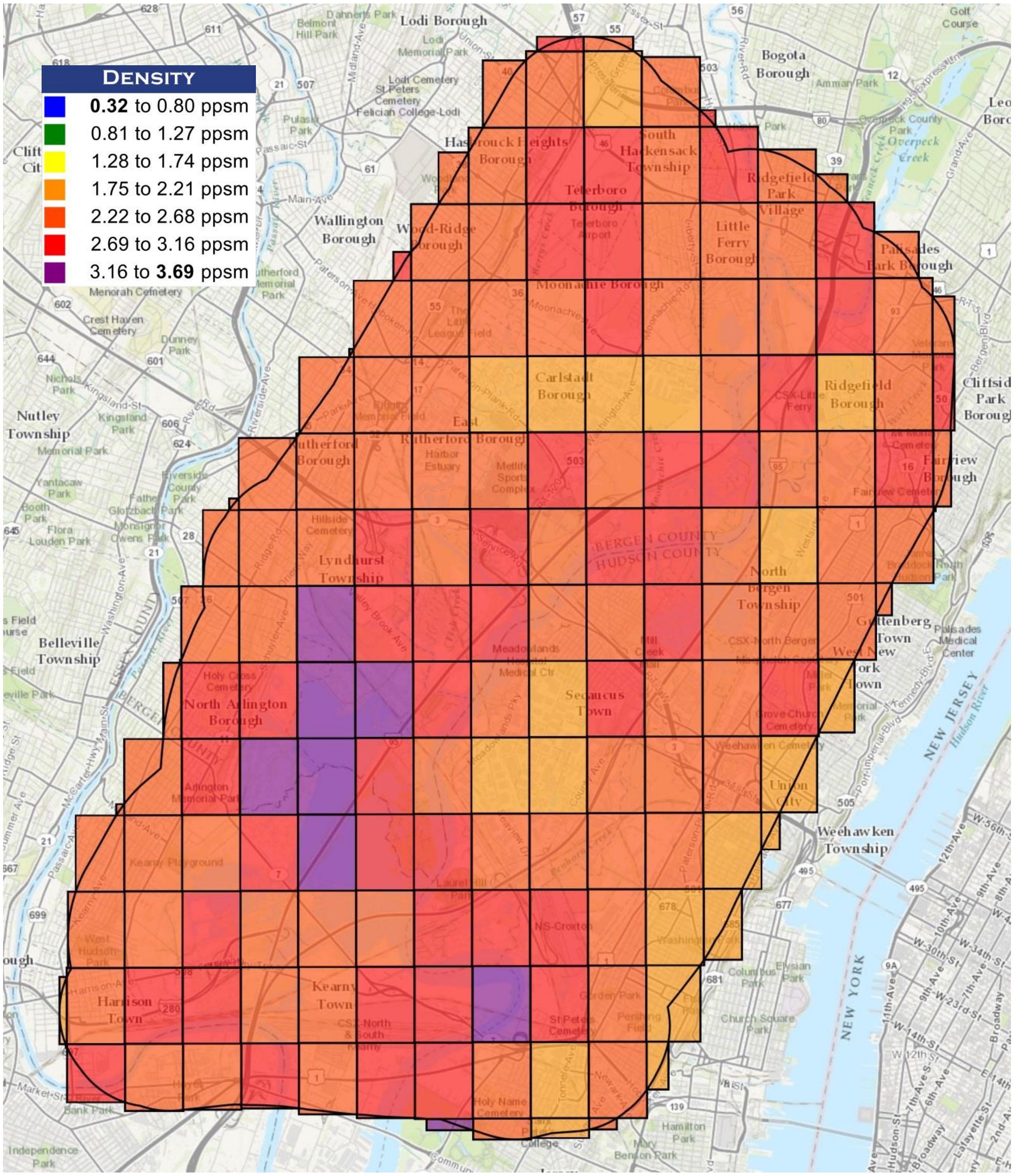


Figure 22: Bare earth point density map for the Hackensack Meadowlands project

Bare Earth Voids at NPS x 2 and NPS x 4

Void testing was also performed on the bare earth (or ground classified) points. Voids identified within the bare earth class may be a good indicator of the laser's ability to penetrate vegetation; however, in cities such as New Jersey, ground voids were expected due to the densely populated urban setting.

Bare earth void testing was calculated in the same manner as first return void testing; with grid cell size equal to NPSx2 and NPSx4. If a bare earth return was present within a defined grid cell, that cell was defined as "populated" and appears green. Defined grid cells which lack bare earth returns were defined as "void" and appear red. Any areas falling within hydro breaklines were excluded from the statistical analysis and appear blue. Complete summary statistics of this analysis are also provided.

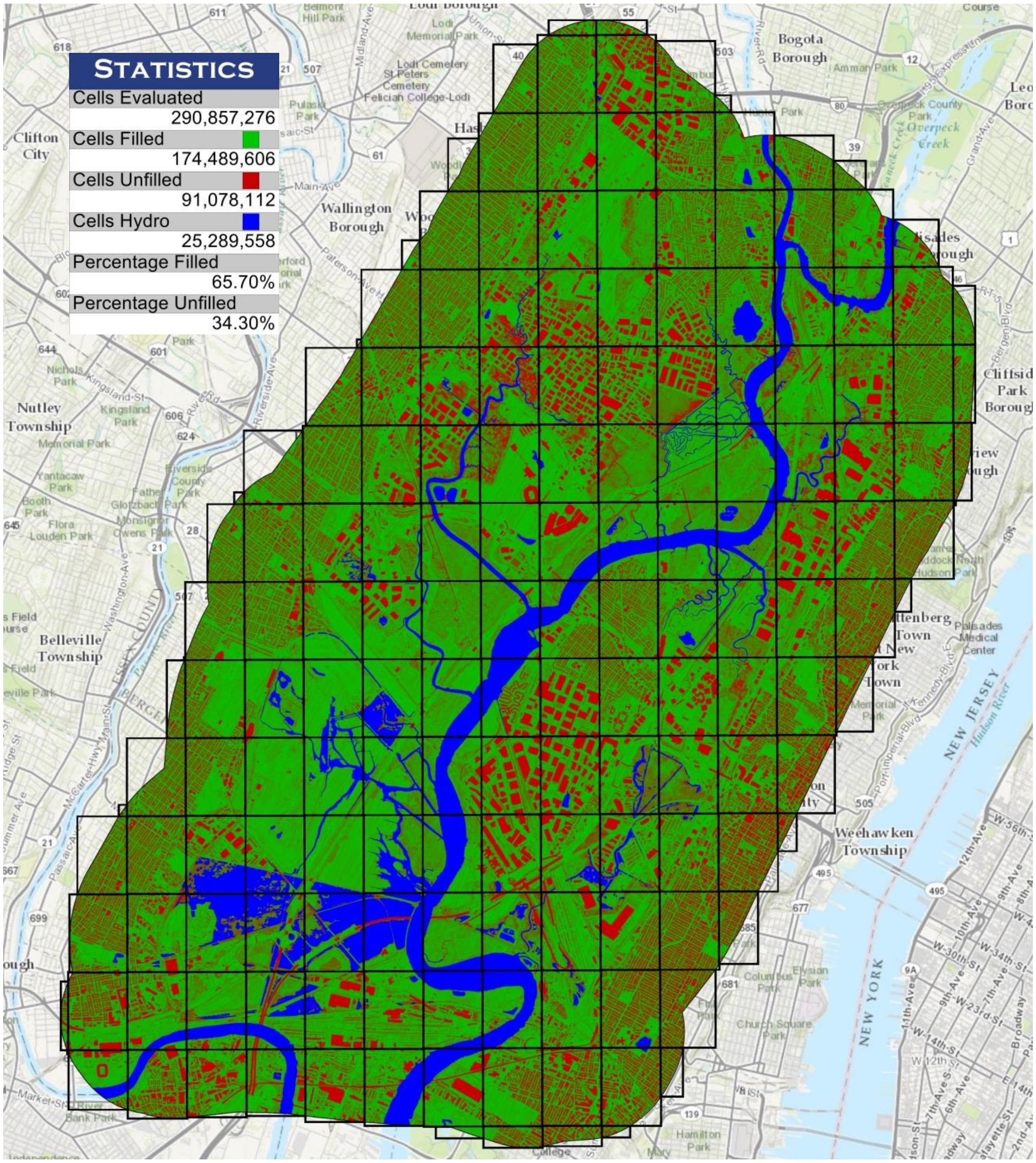


Figure 23: Bare earth voids with grid cell size NPSx2

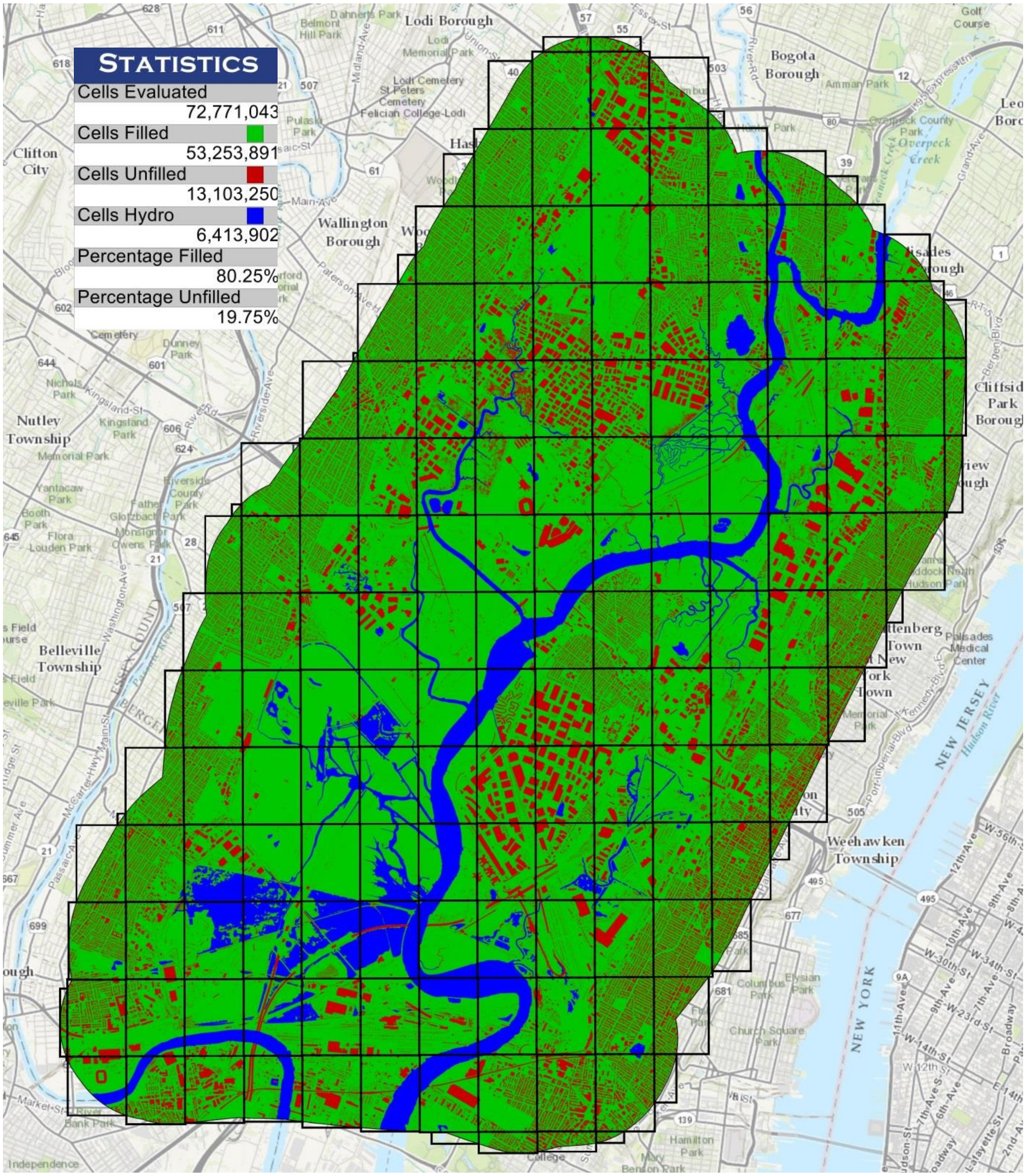


Figure 24: Bare earth voids with grid cell size NPSx4

Intensity Map

Normalized intensity images were generated for each delivered tile and draped over the tile index to form the FOCUS™ intensity map. This graphic may display potential problems with recorded intensity values found in the LAS files.

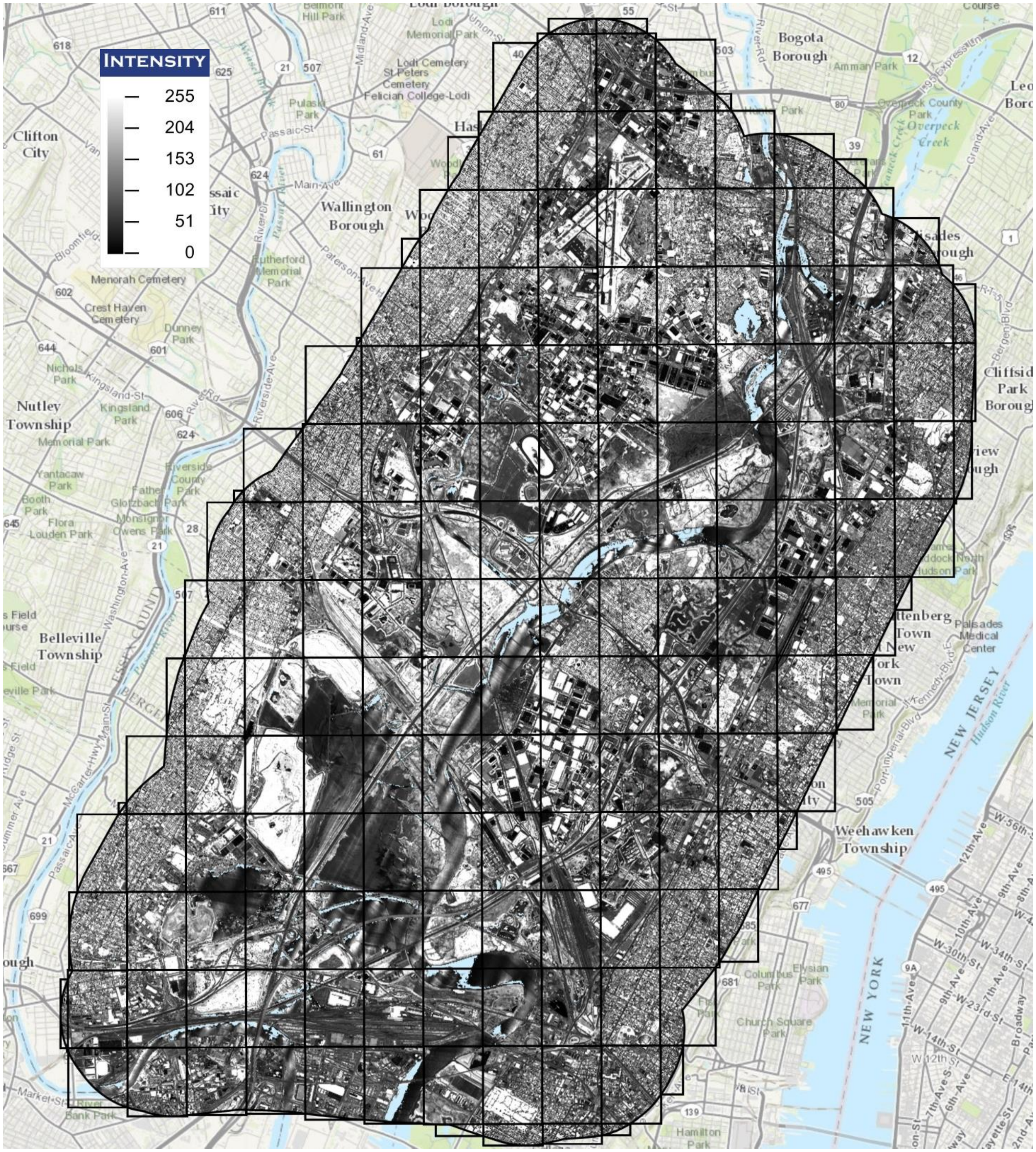
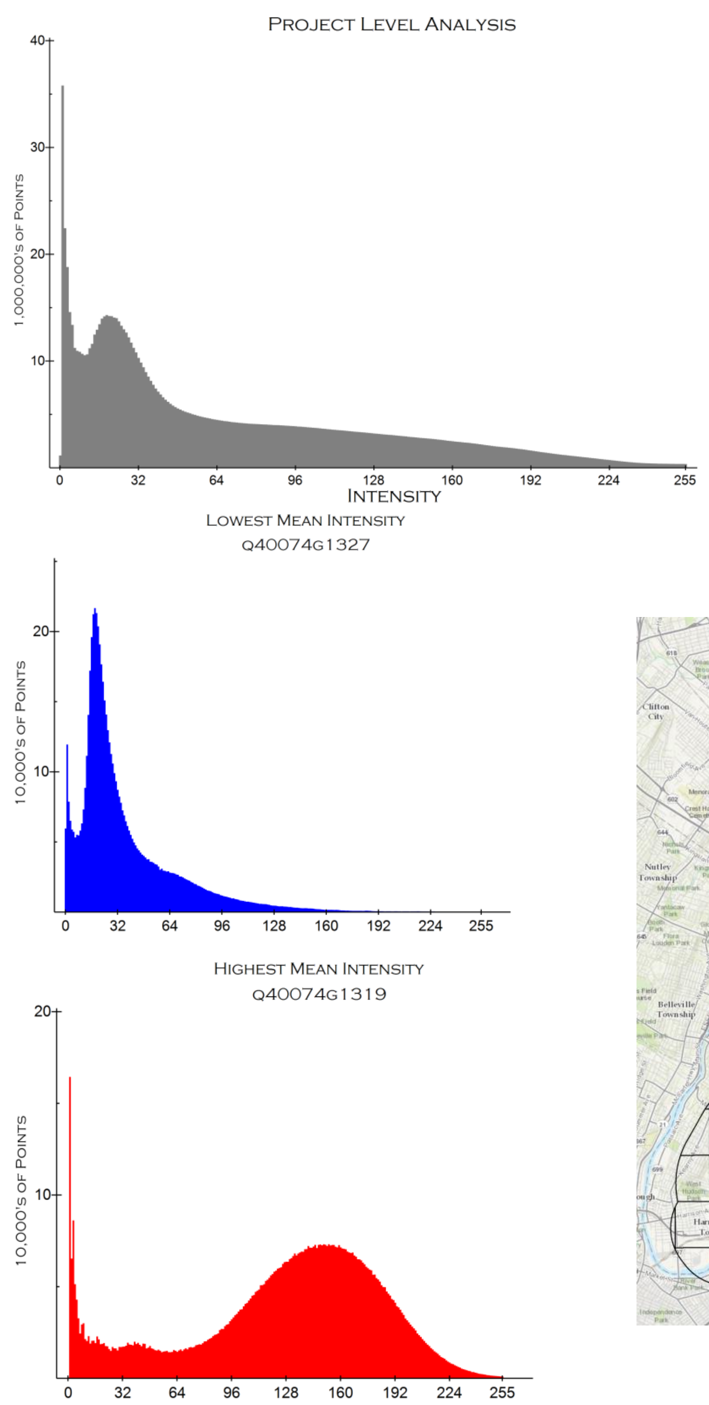


Figure 25: FOCUS™ Intensity map for the Hackensack Meadowlands project

Intensity Analysis

A histogram of the first return intensities was also provided, and individual tiles with the highest and lowest mean intensities were highlighted. Note that actual intensity characteristics may vary significantly based on the project area and the sensor used for acquisition.



Statistics	
Project Mean Intensity	70.4
Lowest Mean Intensity	36.7
Highest Mean Intensity	126.3

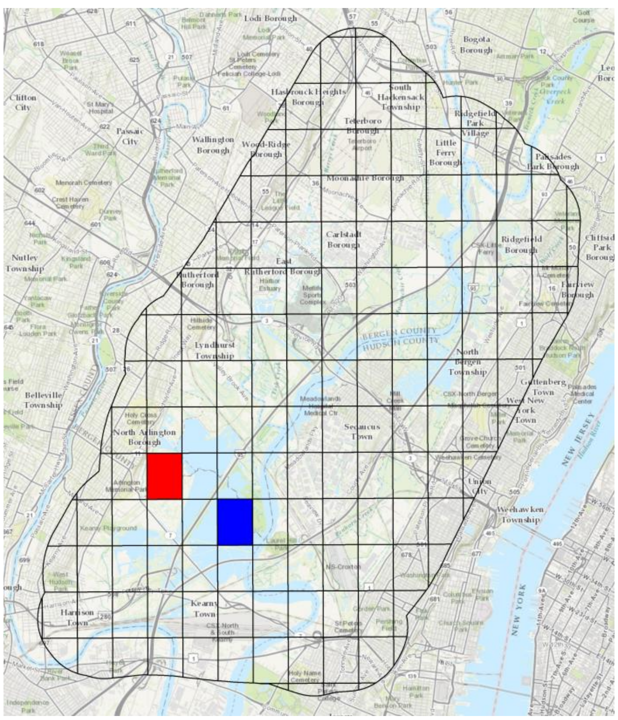


Figure 26: Results of FOCUS™ intensity analysis of the Hackensack Meadowlands LiDAR dataset

Breakline Map

This graphic depicts the location of all hydro breaklines created for the project. The area within closed breaklines around ponds and lakes, and double line drains for large streams are rendered in blue and overlaid on a screened project background map for quick orientation.

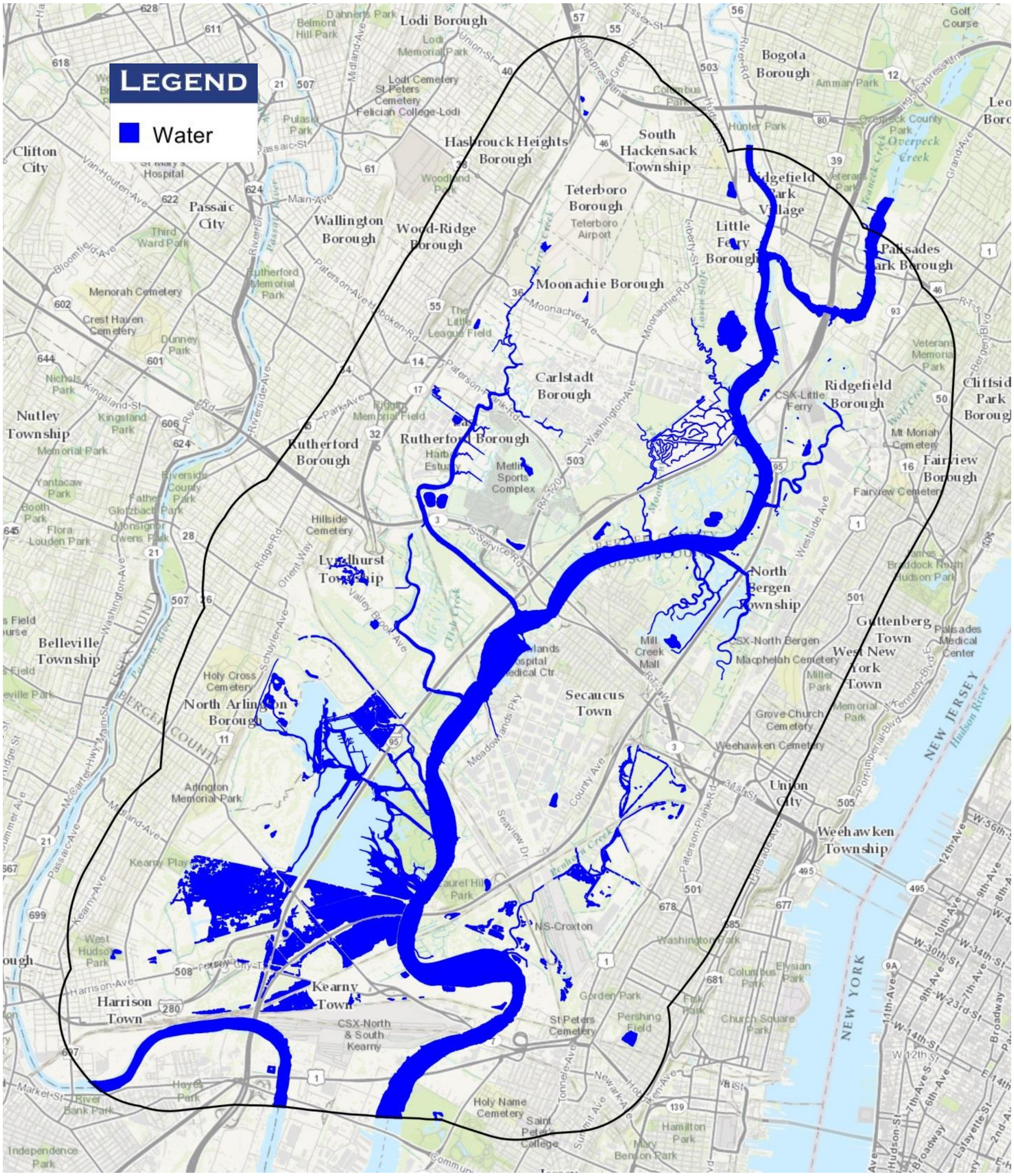


Figure 27: Map of hydro breaklines within the Hackensack Meadowlands survey site

Calibration

The accuracy of the LiDAR point cloud may be affected by systematic errors or scaling, or by variable errors resulting from GNSS conditions including baseline length, number of satellites, and values of Position Dilution of Precision (PDOP). In order to develop a homogenous elevation surface for the project area, effort was taken to remove sources of both systematic and variable error. Once the LiDAR point cloud was consistent between flight lines and missions, the data was tied to the ground surface using ground survey calibration points dispersed throughout the project area.

This graphic depicts the results of the final calibration of the ground surface. All ground survey calibration points are shown as solid circles centered about their horizontal position, are scaled by the amount of relative error at each point (larger circles represent larger errors), and are color coded by the direction of the error (whether the LiDAR surface is higher or lower than the ground survey calibration point). The statistical analysis of this final calibration is included in tabular form with the graphic.

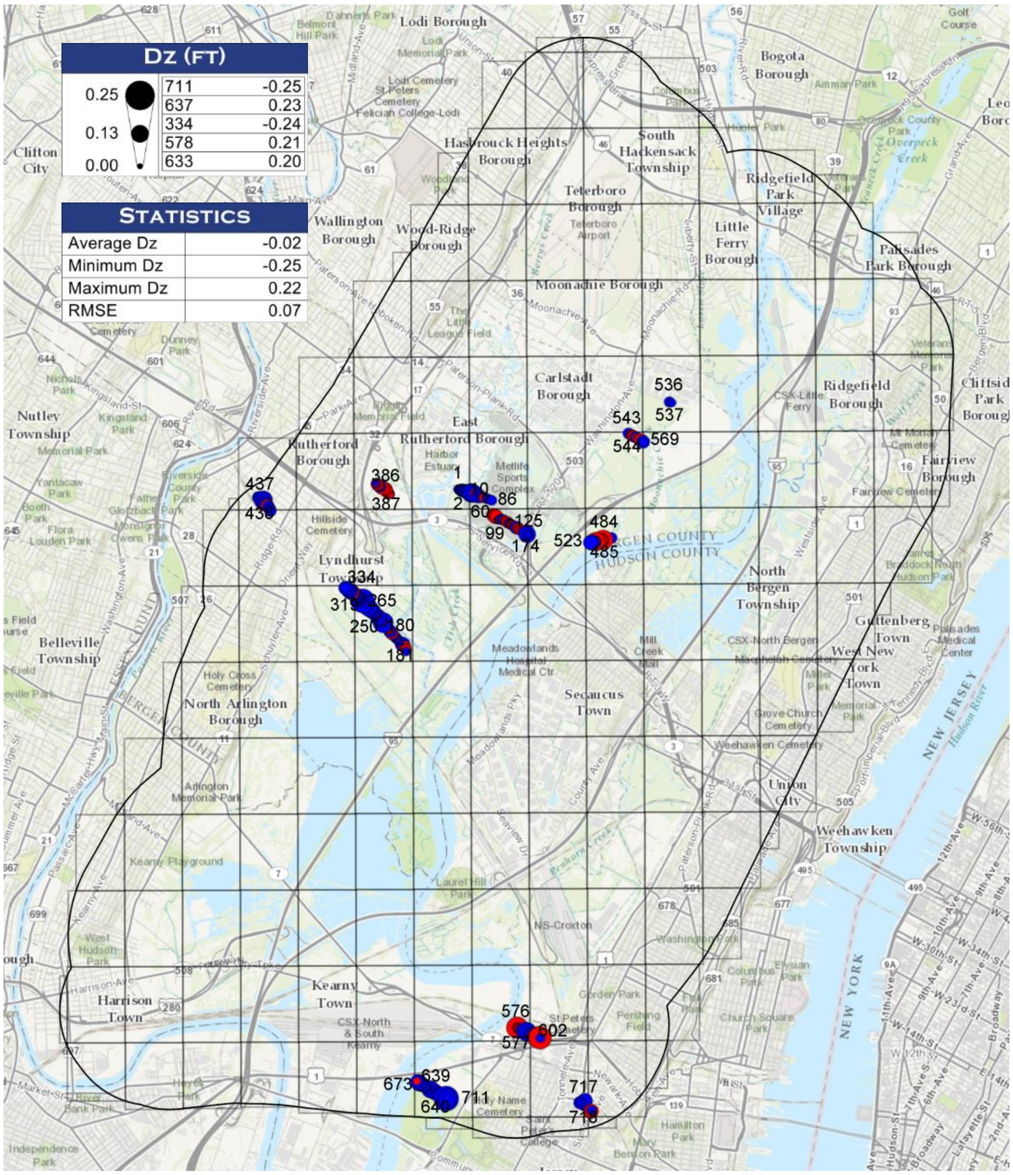


Figure 28: Calibration result map

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 Absolute Accuracy

Absolute accuracy was assessed using reporting designed to meet guidelines presented in the FGDC National Standard for Spatial Data Accuracy[4]. Absolute accuracy assessment compares known ground control point data collected on open, bare earth surfaces with level slope (<20°) to the triangulated ground surface generated by the LiDAR points. It 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* σ), as shown in Table 9.

The mean and standard deviation (sigma σ) of divergence of the ground surface model from ground survey 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 Hackensack Meadowlands survey, 750 ground survey points were collected in total resulting in an average accuracy of-0.016 feet (-0.005 meters) (Figure 29).

Table 9: Absolute accuracy

Absolute Accuracy	
Sample	750 points
Average	-0.016 ft -0.005 m
Median	-0.016 ft -0.005 m
RMSE	0.065 ft 0.020 m
Standard Deviation (1σ)	0.064 ft 0.019 m
1.96σ	0.125 ft 0.038 m

[4] Federal Geographic Data Committee, Geospatial Positioning Accuracy Standards (FGDC-STD-007.3-1998). Part 3: National Standard for Spatial Data Accuracy. http://www.fgdc.gov/standards/projects/FGDC-standards-projects/accuracy/part3/chapter3

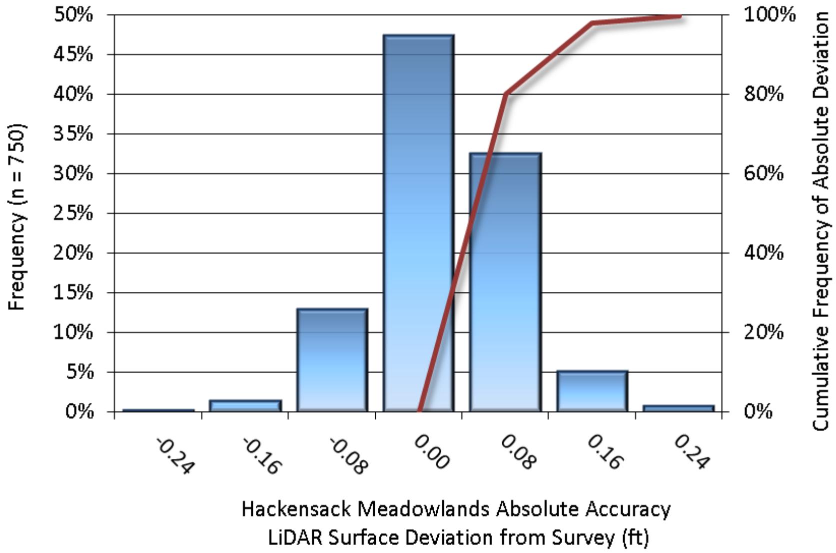


Figure 29: Frequency histogram for LiDAR surface deviation from ground survey point values

LiDAR Vertical Relative 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 Hackensack Meadowlands LiDAR project was 0.090 feet (0.027 meters) (Table 10, Figure 30).

Table 10: Relative accuracy

Relative Accuracy	
Sample	45 surfaces
Average	0.090 ft 0.027 m
Median	0.089 ft 0.027 m
RMSE	0.090 ft 0.027 m
Standard Deviation (1σ)	0.006 ft 0.002 m
1.96σ	0.011 ft 0.003 m

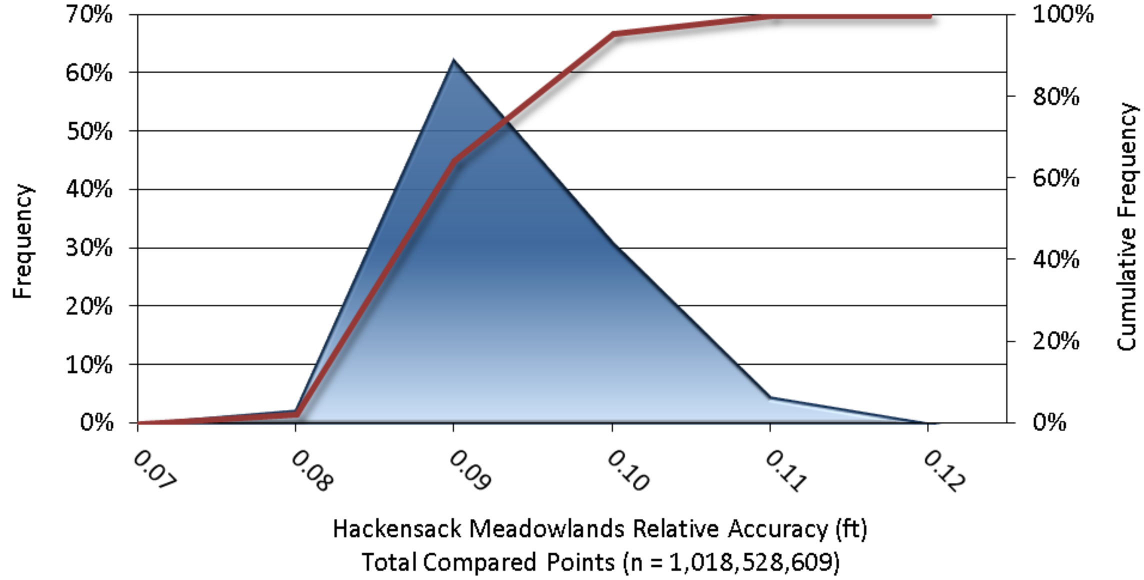


Figure 30: Frequency plot for relative vertical accuracy between flight lines

Surveyor's Certificate

I, Nickolas R. Fusco, being a Professional Land Surveyor in the State of New Jersey, hereby certify to the best of my professional knowledge belief that the survey methodologies and results, attached as part of this report, were performed and obtained utilizing commonly acceptable survey standards, practices and procedures. The field survey portion of this project was accomplished on April 4, 2104 through April 10, 2014

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

May 14, 2014

Nickolas R. Fusco
Professional Land Surveyor Number 27711

Expires 4/30/2016

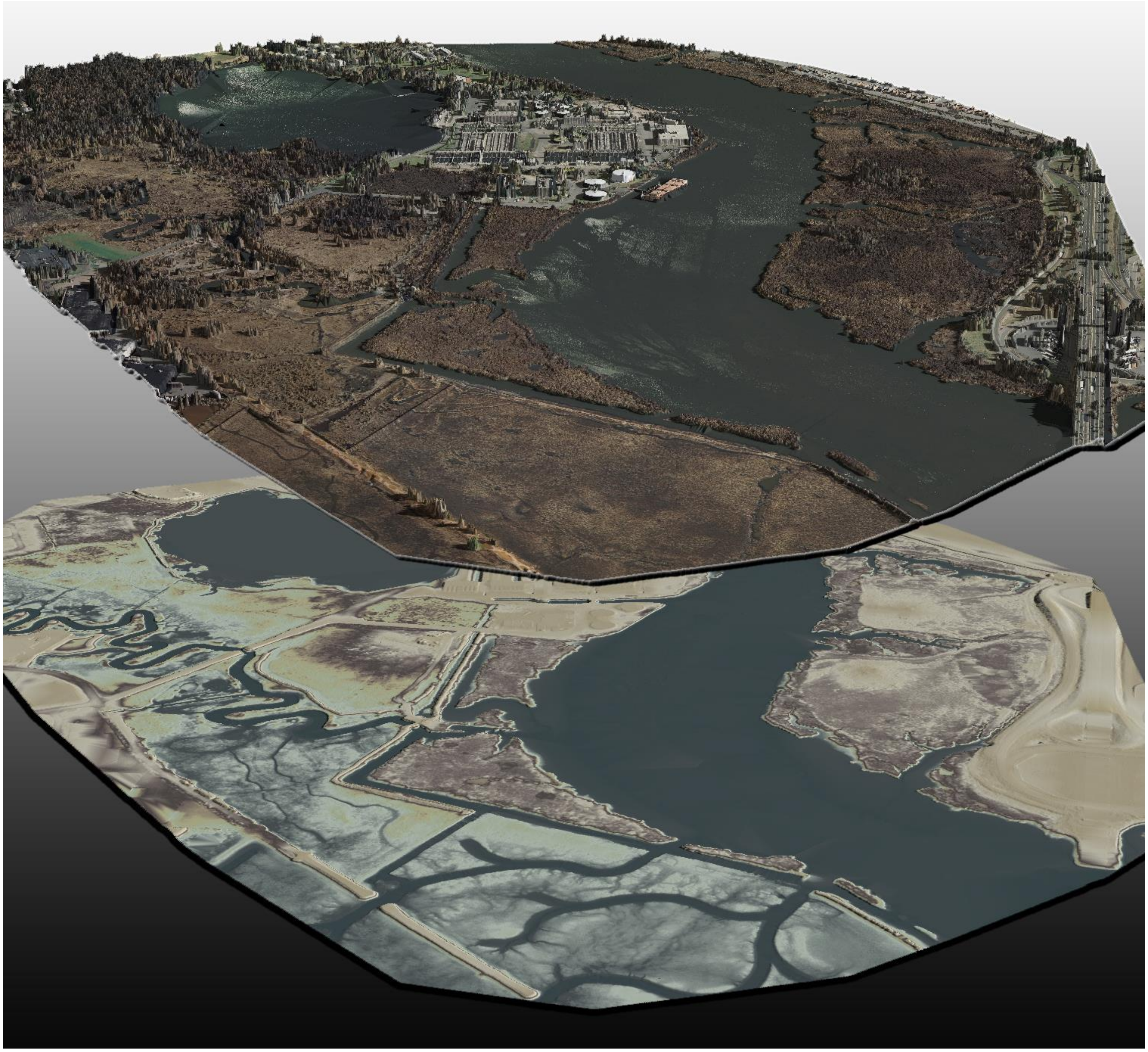


Figure 31: These images show the water treatment plant along the Hackensack River. The bottom image is the bare-earth model colored by elevation, while the top image is the gridded, highest hit model draped with NAIP imagery.

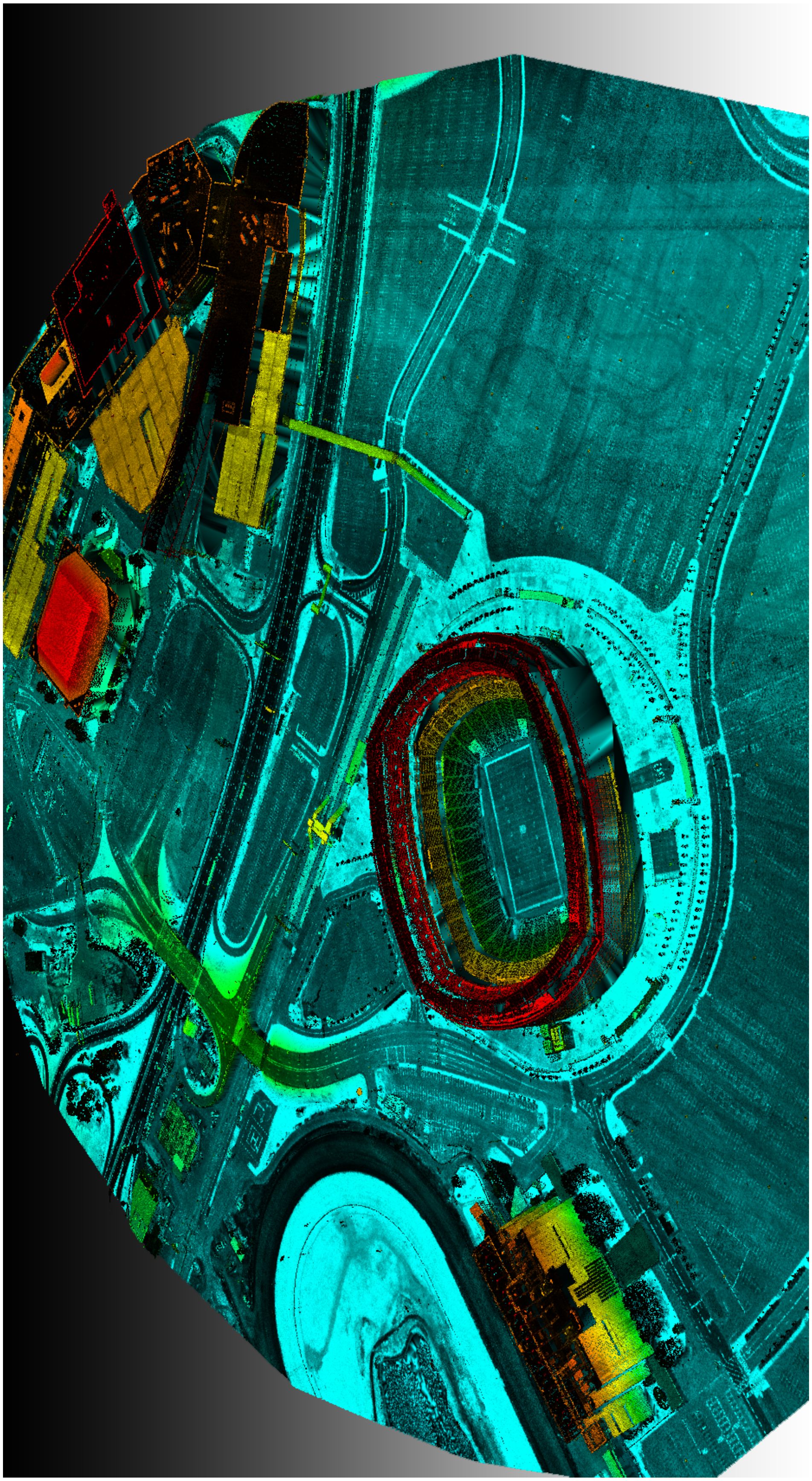


Figure 32: This image shows a view of MetLife Stadium and surrounding areas. The 3D LiDAR point cloud is colored by intensity and elevation.

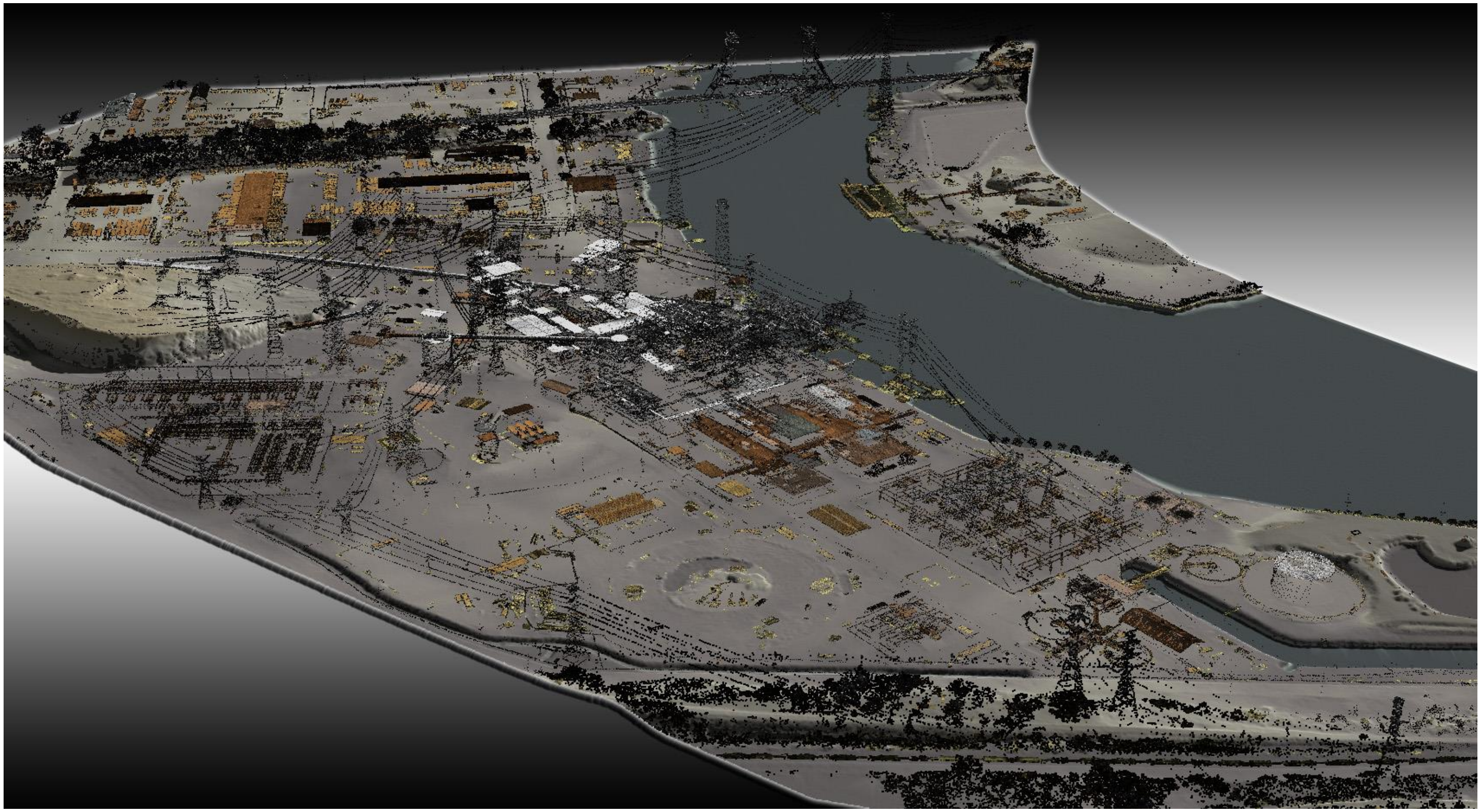


Figure 33: This image shows a view of the Hackensack River power plant. The image is created from the gridded, bare earth model colored by elevation and overlaid with the default classified LiDAR point cloud.

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 $\pm 15^{o}$ 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.

Appendix B – Glossary of LiDAR Terms

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-sigma (σ) Absolute Deviation: Value for which the data are within two standard deviations (approximately 95th percentile) of a normally distributed data set.

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 RTK 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, 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 - 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).

Amplitude – Amplitude represents the maximum distance of the alternating NIR wave, measured from the position of equilibrium to either the crest or trough of the wave.

Attenuation – The loss of signal strength as the signal travels through a medium. Attenuation can be thought of as the opposite of amplification.

Bare Earth Surface – A terrain surface that is free from vegetation, buildings, vehicles, bridges, and other man-made features. A bare earth surface is meant to be an accurate representation of natural ground.

Beam Divergence – The energy emitted by the laser within a LiDAR sensor leaves the sensor as a very narrow beam of light, but increases in diameter along the path to the ground. The angle at which the beam increases is known as the beam divergence. This divergence is typically measured in the units of milliradians (mrad). It is common for current sensors to have a beam divergence ranging between 0.1 and 1.0 mrads. At 0.4 mrads, the diameter of the beam 1,000 meters away from the sensor would be 40 cm.

Breakline – A line that defines areas of discontinuity, or sharp breaks in the natural ground surface. Breaklines are often placed at toes of slope, along ridgelines, and at the edges of water in lakes, ponds, streams, and the coast.

Class – See Feature Class.

Consolidated Vertical Accuracy (CVA) – CVA for a LiDAR elevation surface is defined as the accuracy of that surface as compared to all land cover ground survey point combinations. It is the consolidation of the FVA and SVA. See also Fundamental Vertical Accuracy and Supplemental Vertical Accuracy.

Corn Rows – Corn rows in a LiDAR elevation surface typically represent a sensor problem during acquisition that results from positive and negative elevation biases in adjacent passes (normally in opposite scan directions) of the scanning mirror. Because of the biases, these errors present the appearance of a plowed field, or rows of corn.

Data Density – A common measure of LiDAR resolution, measured as points per square meter (ppsm).

Digital Elevation Model (DEM) – a DEM is a digital representation of the earth's surface. See also Digital Surface Model and Digital Terrain Model.

Digital Surface Model (DSM) – A DSM is most often used to describe a first return LiDAR surface that would typically include all natural and man-made features (e.g., trees, brush, buildings, etc.) that lie above the natural ground surface. See also Digital Elevation Model and Digital Terrain Model.

Digital Terrain Model (DTM) – A DTM is most often used to describe a digital representation of the earth's surface that includes both mass points and breaklines. See also Digital Elevation Model and Digital Surface Model.

Discrete Returns – LiDAR sensors are known as discrete return sensors when they are set to record individual returns at precisely referenced points in time and 3D space. Most current LiDAR sensors can measure and record 4 discrete returns per outgoing laser pulse. Returns are typically recorded as first, second, third, and last (as opposed to fourth) returns. This is significantly different from full waveform technology discussed below.

Echo – See Return.

Enhanced Nominal Ocular Hazard Distance (eNOHD) – The eNOHD represents a safe ocular distance for laser operation. This distance is reduced from the NOHD by the assumption that a person on the ground is using binoculars to view the aerial platform during acquisition, which would effectively increase the potential damaging effects of the sensor's laser. This is also termed binocular eye safe range. See also Nominal Ocular Hazard Distance.

Feature Class – A feature class is a homogenous collection of LiDAR returns that represent a specific type of feature imaged with LiDAR. Common feature classes within a typical LAS file structure include Class 1 – Default, or non-ground, Class 2 – Bare Earth, Class 8 – Model Key, and Class 9 – Water.

Field of View (FOV) – Refers to the angular measure of the scan pattern of the mirror that directs the laser's energy from the sensor to the ground. The FOV is measured perpendicular to the flight of the aircraft. The angular measure of the complete scan on both sides of nadir is known as the full angle FOV. The angular measure of the scan from nadir to the left or right side is known as the half angle FOV. The FOV for current LiDAR sensors are typically selectable during flight planning and many sensors have a maximum full angle FOV of approximately 75 degrees.

Frequency – For cyclic processes like the propagation of a laser beam from a LiDAR sensor, the frequency is defined as the number of cycles per unit time. The frequency is most often provided in terms of cycles per second, which represents the unit of frequency in Hertz (Hz).

Full Waveform – LiDAR sensors that record a near-continuous digital representation of the returned laser signal are known as full waveform. This is significantly different from the discrete returns discussed above.

Fundamental Vertical Accuracy (FVA) – The FVA for a LiDAR elevation surface is defined as the accuracy of that surface in open terrain where the LiDAR surface is thought to be most reliable. See also Supplemental Vertical Accuracy and Consolidated Vertical Accuracy.

Galvanometer – A galvanometer is a sensitive ammeter that is used within a LiDAR sensor to accurately measure the swing angle of the scanning mirror as a function of time.

Hertz (Hz) – A unit of measure equal to the number of cycles per second. A rate of 100 Hz would be equal to 100 cycles per second.

Illuminated Footprint – The illuminated footprint is a measure of the theoretical diameter of the laser beam as it is reflected off a surface that is perpendicular to the path of the beam at the planned flying height. It is a function of both the beam divergence and the planned flying height above ground. Common illuminated footprints for current sensors range from a few decimeters, to a meter or more in diameter.

Inertial Measurement Unit (IMU) – See Inertial Navigation System.

Inertial Navigation System (INS) – An INS is used to accurately measure the three dimensional rotation of a LiDAR sensor at all times during flight. The INS uses a combination of accelerometers to measure motion, and gyroscopes to measure rotation within an Inertial Measurement Unit (IMU). When combined with GPS positioning, the INS can provide the very accuracy position, orientation, and velocity of the sensor at all times. The typical sampling rate of current INSs is 200 Hz, which provides updates 200 times per second during flight.

Intensity – Current LiDAR units record the reflectance of the surfaces illuminated by the sensor's laser. This measure of reflectance is referred to as the intensity of the return. Intensity is mainly a function of the characteristics of the surface (for example, concrete has a significantly higher reflectance as compared to asphalt), but it is also affected by the incidence angle that the laser beam makes with the footprint surface, the path length of the beam, the sensor's laser optics and receiver characteristics, and atmospheric attenuation.

Kilohertz (kHz) – A kilohertz is a unit of electromagnetic wave frequency equal to 1,000 Hertz. In LiDAR technology, the frequency of laser pulses emitted for ground measurement is commonly referred to in the units of kilohertz. For example, a LiDAR sensor might be pulsed at 100 kHz for data acquisition, and this would be equivalent to 100,000 measurements per second of flight.

Land Cover Classes – Land cover types and classifications as defined by the U.S. Geological Survey.

LAS – The binary data file that is used to store LiDAR point data records. A LAS file is hardware independent and is recognized by most LiDAR software platforms on the market today. The LAS structure was developed and is maintained by the ASPRS LiDAR Committee.

Laser Repetition Rate – Defined as the number of emitted pulses per second from the laser within a LiDAR sensor. Specified in units of kHz, current sensors operate in a general maximum range of 150 to 500 kHz. This is also known as the pulse repetition frequency (PRF).

LiDAR – An acronym for Light Detection and Ranging. LiDAR technology provides an efficient means of measuring three-dimensional points on the ground along with the amount of energy reflected from the LiDAR sensor's laser. A LiDAR sensor is a complex combination of a number of electrical systems including a laser, scanning optics, a photodetector and receiver optics, and a position and orientation system.

Minimum Discrimination Distance – This distance is the minimum separation of reflections along the path of the laser beam that can be resolved by the LiDAR sensor. This can be thought of as a "dead zone" along the path such that once one return is logged by the sensor, the detection of another return is not possible until the laser travels this defined distance along its path. This is a function of the electronics of a discrete return sensor and the disadvantages of this are removed with a full waveform sensor. This is also known as the vertical discrimination distance, with typical measurements ranging from sub-meter to 3.5 meters or more with today's LiDAR sensors.

Multiple Returns – Multiple returns refer to the sensor's ability to record multiple discrete returns along the laser's path. This is very useful for penetrating overhanging trees, or seeing the ground below the tops of electrical conductors or utility poles. Based on the theory that a portion of the laser's energy will be reflected from above ground features, but the remainder of the energy will continue on its path to the ground. More energy might be reflected off a branch or additional vegetation during this path and therefore recorded as a second or third return. Ideally enough energy will make it to the ground surface where it will be reflected and recorded as a last return. Most sensors today have the ability to record up to four returns for each outgoing laser pulse.

Multiple Pulse in Air (MPiA) – MPiA technology refers to LiDAR sensors that have the ability to fire the next laser pulse prior to receiving the reflection of the previous return. The name is derived from the sensor's ability to have multiple pulses in the air at one time, yet accurately equate the right reflected return with the correct outgoing pulse. MPiA technology has the significant advantage of increased point density as compared to a single pulse system, or allowing higher flights at any given point density, which results in a wider swath width and decreased acquisition times.

Nadir – The direction pointing straight down from the bottom of the aircraft.

Nanometer – A unit of length in the metric system equal to one billionth of a meter.

Nanosecond – A unit of time equal to one billionth of a second. At the nominal speed of light of 299,792,458 meters per second, the laser beam in LiDAR will travel about 30 cm in one nanosecond.

National Standard for Spatial Data Accuracy (NSSDA) – The NSSDA implements a statistical and testing methodology for estimating the positional accuracy of points on maps and in digital geospatial data, with respect to geo-referenced ground positions of higher accuracy[5]. It represents the most popular accuracy standard for use in testing and reporting the accuracy for today's LiDAR projects.

Native Density – The number of pulses emitted by the LiDAR system, commonly expressed as pulses per square meter.

Near Infrared (NIR) – Most terrestrial LiDAR sensors today use a solid-state Nd:YAG (neodymium-doped yttrium aluminum garnet) laser that produces non-visible light in the near infrared region of the electromagnetic spectrum at 1,064 nanometers (nm). The visible spectrum corresponds to wavelengths ranging from 400 (violet) to just over 700 nm (red), and that portion of the spectrum just beyond red is known as the near-infrared region, extending from 700 nm to 1 millimeter (mm).

Nominal Ocular Hazard Distance (NOHD) – The NOHD is the distance from the LiDAR sensor at which point the laser's energy falls below the maximum permissible exposure (MPE) limit, or in other words, the distance at which the laser beam from the LiDAR sensor will not result in damage to the eyes. It might also be termed the eyesafe distance. See also Enhanced Nominal Ocular Hazard Distance.

Nominal Point Spacing (NPS) – The NPS is the nominal linear dimension between the centers of consecutive laser points on the ground. The NPS is typically presented in the units of meters for LiDAR, even when the units selected for the project are not metric units. The NPS is mathematically related to the point density by the following equation: NPS = Square Root (1 / Density) A project with 0.7 meter nominal point spacing would be equivalent to a density of 2 ppsm.

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

Photon – A particle without mass that travels with a certain energy and momentum. The near infrared rays in a LiDAR beam are comprised of individual photons, which travel through space at 186,282 miles per second.

Point Cloud – A collection of three-dimensional points, the relative intensity of the returns for these points, and metadata associated with their acquisition.

Point Data Format – An ID within the LAS file structure that corresponds to the point data record format.

Point Density – The nominal point density refers to the number of laser returns within a given unit area. The density is almost always quoted in units of points per square meter (ppsm), which is representative of the number of returns typically found in a square cell measuring one meter by one meter. The point density is mathematically related to the nominal point spacing by the following equation: Density = 1 / NPS2. A project with a nominal point density of 4 ppsm would be equivalent to a nominal point spacing of 0.5 meters.

Points per Square Meter (ppsm) – The nominal number of returns within a square cell measuring one meter by one meter, with this number presented as the density in units of ppsm.

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 computer and applied after the fact during processing. This type of ground survey is accurate to 1.5 cm or less.

Pulse Repetition Frequency (PRF) – See Laser Repetition Rate.

Pulse Returns – The rate at which laser pulses are emitted from the sensor; typically measured in thousands of pulses per second (kHZ).

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[5] Geospatial Positioning Accuracy Standards Part 3: National Standard for Spatial Data Accuracy published by the Subcommittee for Base Cartographic Data, Federal Geographic Data Committee.

Pulse Width – The pulse width is the measure of time that the laser diode is energized during the generation of an individual laser pulse. This width is typically measured in the units of nanoseconds. At the speed of light, one nanosecond in pulse width is about 30 centimeters in length.

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.

Reflectance – The reflectance of the typical 1,064 nm NIR laser beam used in LiDAR can vary substantially with typical reflectivities ranging from 5% for new asphalt, 20% for asphalt shingles, 30% for concrete, 50% for mixed forest, and 70 to 90% for snow. See also Intensity.

Refractive Index – The ratio of the speed of light in a vacuum to the speed at which light travels in a material is known as the refractive index (n) of the material. The refractive index for air for visible light is about 1.0003. The refractive index for water at 20 degrees C is 1.33 and this index is very important to topo-bathymetric LiDAR sensors used in bathymetric applications.

Return – Refers to the measurable reflection of the laser signal from an object on or near the ground that is provided in 3D space, (also known as an echo).

Root Mean Square Error (RMSE) – A statistical value equal to the square root of the average (mean) of the squares of the individual errors within a test. Individual errors in LiDAR refer to the difference between a known position on the ground (horizontal position or elevation) and the position represented within the LiDAR surface. In terms of the horizontal position, the value is often referred to as RMSEXY or RMSER. In terms of elevation, the value is most often referred to as RMSEz.

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

Scan Rate – The rate at which a scanning device (in the case of LiDAR the scanning mirror) samples the field of view of the sensor, in units of cycles per second, or Hertz.

Signal to Noise Ratio (SNR) – The ratio of desired signal level to the background noise inacquisition, with higher values generally more desirable. The SNR is a unitless number.

Smoothed Best Estimate of Trajectory (SBET) – The estimated trajectory, or sensor path, in three dimensional space as a function of time during LiDAR acquisition. The SBET is normally determined from post processing the AGPS and inertial navigation information captured during the LiDAR acquisition.

Speed of Light – The speed of light in a vacuum is equal to 299,792,458 meters per second, or about 186,282 miles per second. This speed is independent of temperature, but it does vary with the density of the medium through which the light is passing. See also Refractive Index.

Supplemental Vertical Accuracy (SVA) – The SVA for a LiDAR elevation surface is defined as the accuracy of that surface in land cover combinations other than open areas. See also Fundamental Vertical Accuracy and Consolidated Vertical Accuracy.

Swath Width – The width of ground coverage acquired in a single pass of the LiDAR sensor. The nominal swath width is a function of the field of view of the sensor and the flying height above terrain and can be determined with trigonometry (W = 2 x H x tan (theta / 2)).

Wavelength – The distance over which the wave from the laser repeats itself. This could be measured from one crest of the wave to the next, or from one trough to the next as these distances will be equal. The number of times this wave repeats itself over a unit of time is known as the frequency.