FOCUS™

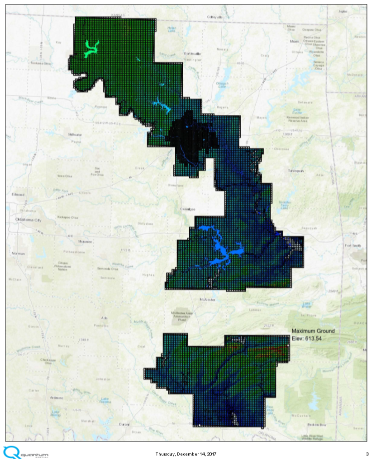
Powered by Quantum Spatial

FOCUS is an acronym for Final Observed and Calculated User Statistics and serves as an important reporting and QC tool for LiDAR projects. As such, this report provides a comprehensive look and evaluation of LiDAR derived elevation products. The software tools that comprise FOCUS are an important part of our QC processes during the development of LiDAR elevation surfaces.

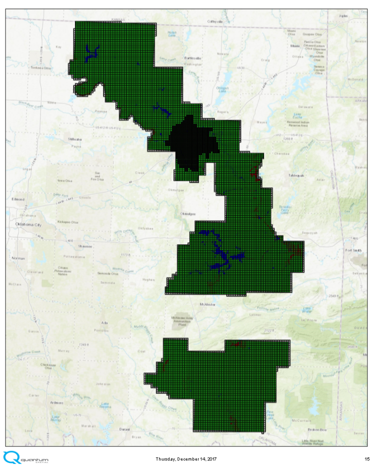
After writing the LAS and associated project files to the delivery media, we run these tools one more time on the actual deliverables to ensure that we are providing a quality product. The results of these final tests are contained in the following document and available for your general review of this dataset.

Appendix A of this document provides a thorough explanation of each of the tests summarized within this report. Appendix B provides a detailed glossary of common LiDAR terminology.

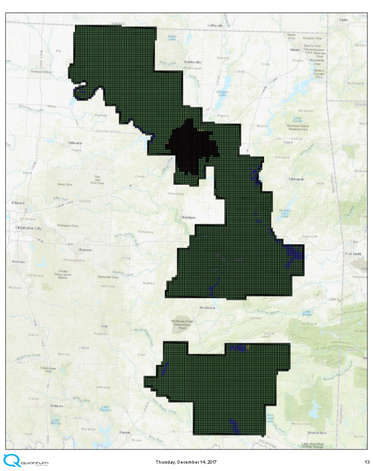
Shaded Relief Map



First Return Voids At NPS*2



First Return Point Density



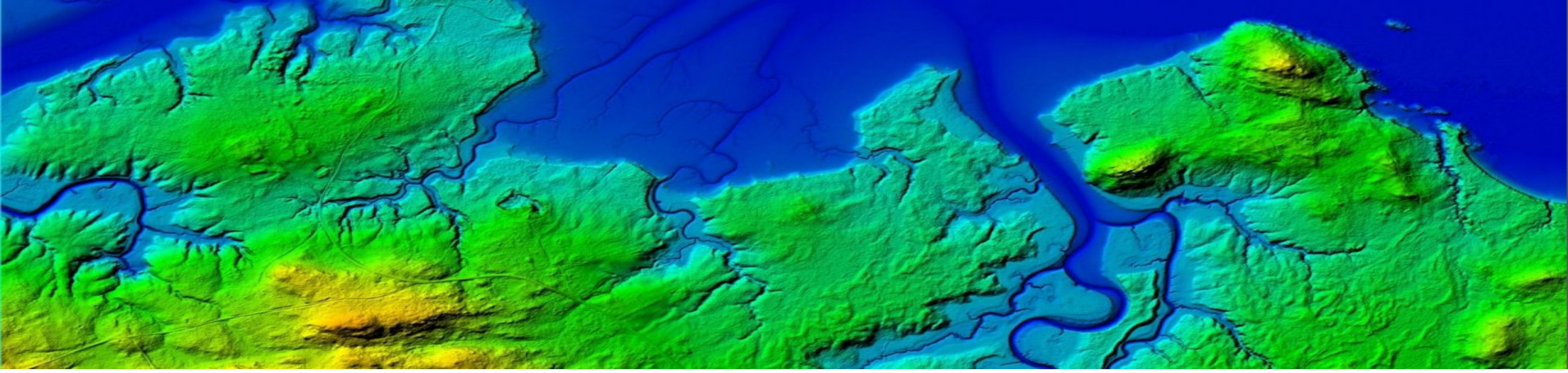


TABLE OF CONTENTS

quantum SPATIAL

Summary

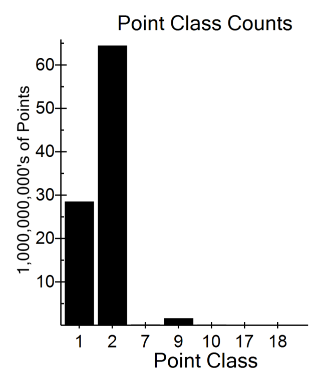
OK_Woodward_FEMA_R6_LiDAR_2016_D17
G17PD00013

Project Information

LAS Version	1.4	12022 of 12022 Tiles
Point Data Format	6	12022 of 12022 Tiles
Projection	(2011) / UTM zone 15N	12022 of 12022 Tiles
Horizontal Datum	NAD83 2011	12022 of 12022 Tiles
Vertical Datum	NAVD88 meters	12022 of 12022 Tiles
Vertical Geoid	height (Meter)	12022 of 12022 Tiles
Minimum Ground	N 3,767,815.01 m E 247,006.04 m	Elev 121.86 m
Maximum Ground	N 3,833,232.40 m E 322,685.66 m	Elev 613.54 m
Planned NPS	0.70 meters	
Project Area	8,605.55 sq mi	
Tile Size	Varies	
Start Of Acquisition	9/14/2011 1:46:40 AM UTC	
End Of Acquisition	4/7/2017 11:21:45 PM UTC	
Tile Boundary Test	Pass	

Point Classification Analysis

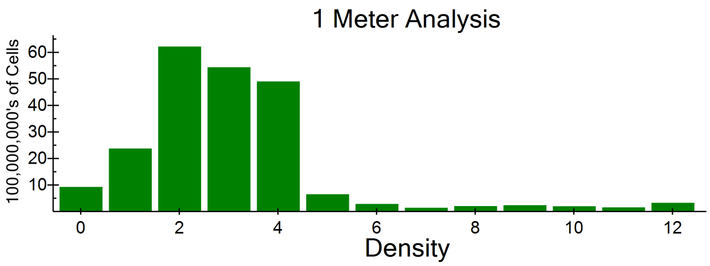
Classification	Point Count[1]	Density[2]	Overlap
Class - All	94,316,626,921	3.90 ppsm	53,690,399,472
Class 1 - Unclassified	28,384,031,286	1.21 ppsm	15,650,308,230
Class 2 - Ground	64,343,844,630	2.75 ppsm	37,989,091,063
Class 7 - Low Points	40,817,790	0.00 ppsm	0
Class 9 - Water	1,494,556,784	0.03 ppsm	51,000,179
Class 10 - Ignored Ground	24,576,447	0.00 ppsm	0
Class 17 - Bridge	14,891,373	0.00 ppsm	0
Class 18 - High Noise	13,908,611	0.00 ppsm	0



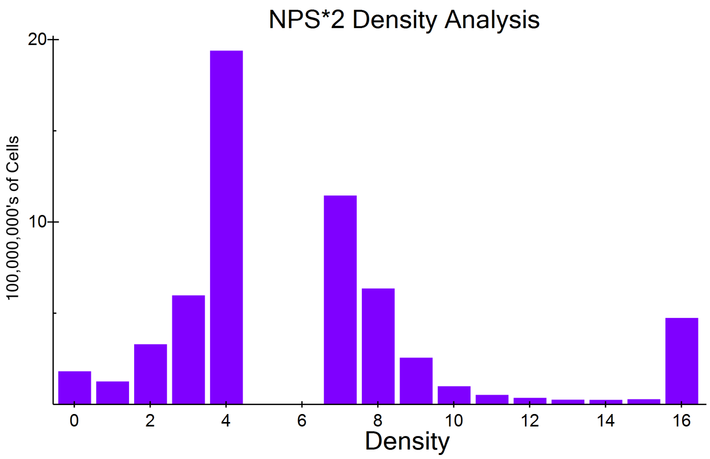
Point Return Statistics

	Point Count[1]		
Return 1 Points	70,867,884,239	Return 5 Points	82,036,158
Return 2 Points	16,908,618,592	Return 6 Points	4,464,240
Return 3 Points	5,509,777,525	Return 7 Points	476,161
Return 4 Points	943,206,702	Return 8 Points	163,304

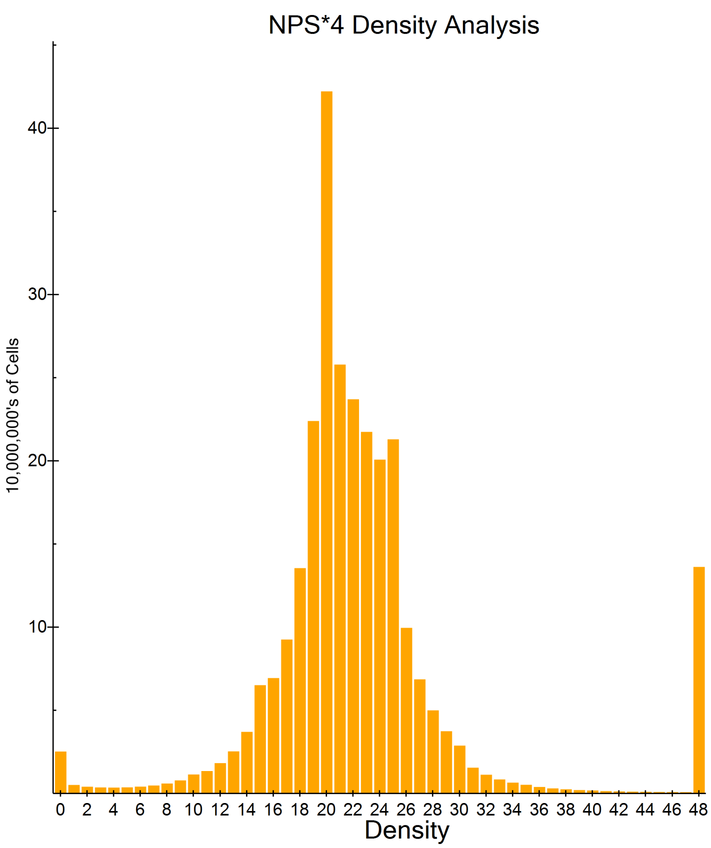
[1]Overlap not included
[2]Results based only on points within AOI. (LAS 1.2, Water excluded)



1 Meter Cell			
Average	3.07	Standard Dev.	2.18
Return Count	# of Cells	Return Count	# of Cells
0	903,247,766	7	118,008,741
1	2,351,627,367	8	181,899,052
2	6,193,246,652	9	214,828,296
3	5,415,651,460	10	176,395,900
4	4,879,001,767	11	133,397,122
5	625,963,662	12+	304,895,885
6	263,160,525		



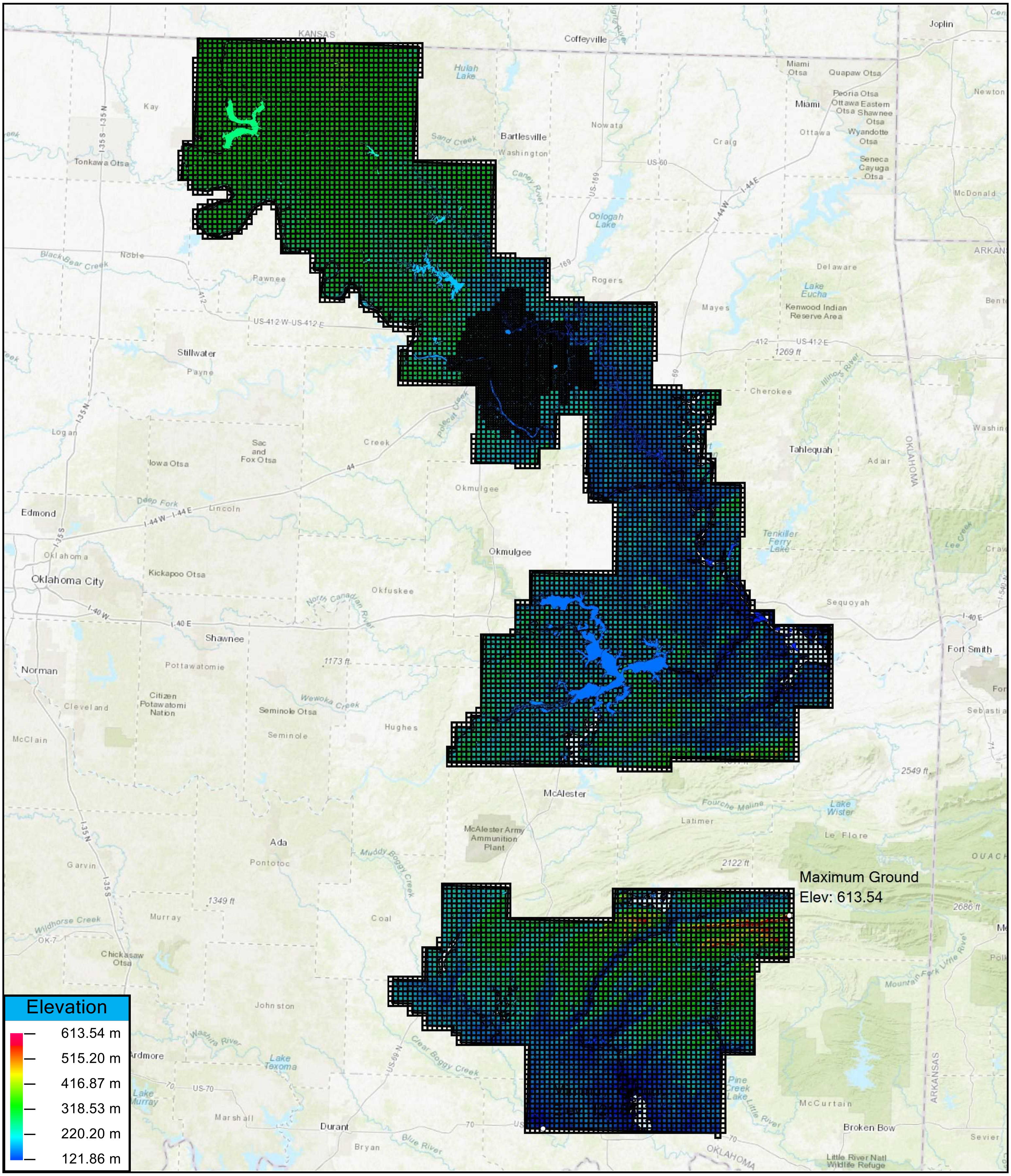
1.4 Meter Cell (NPS*2)			
Average	6.02	Standard Dev.	3.87
Return Count	# of Cells	Return Count	# of Cells
0	178,103,686	9	252,747,128
1	122,582,908	10	96,084,944
2	326,366,053	11	49,002,602
3	594,439,858	12	32,502,774
4	1,936,298,232	13	22,410,779
5	2,966,205,950	14	21,789,656
6	2,245,199,399	15	25,238,505
7	1,141,831,773	16+	470,723,533
8	632,119,007		



2.8 Meter Cell (NPS*4)			
Average	24.07	Standard Dev.	14.27
Return Count	# of Cells	Return Count	# of Cells
0	24,833,948	25	212,568,760
1	4,719,898	26	99,192,203
2	3,678,005	27	68,243,216
3	3,230,292	28	49,577,596
4	3,143,948	29	37,042,188
5	3,312,800	30	28,398,049
6	3,711,128	31	15,106,856
7	4,404,658	32	10,877,199
8	5,583,018	33	8,069,939
9	7,491,142	34	6,145,111
10	11,034,373	35	4,836,575
11	13,113,476	36	3,512,187
12	17,876,951	37	2,684,323
13	24,915,545	38	2,138,010
14	36,651,648	39	1,667,330
15	64,734,030	40	1,425,083
16	68,994,988	41	1,009,392
17	92,189,542	42	838,217
18	135,127,511	43	673,795
19	223,604,702	44	596,245
20	421,789,246	45	509,706
21	257,519,836	46	464,090
22	236,663,095	47	420,659
23	217,057,027	48+	135,854,512
24	200,379,207		

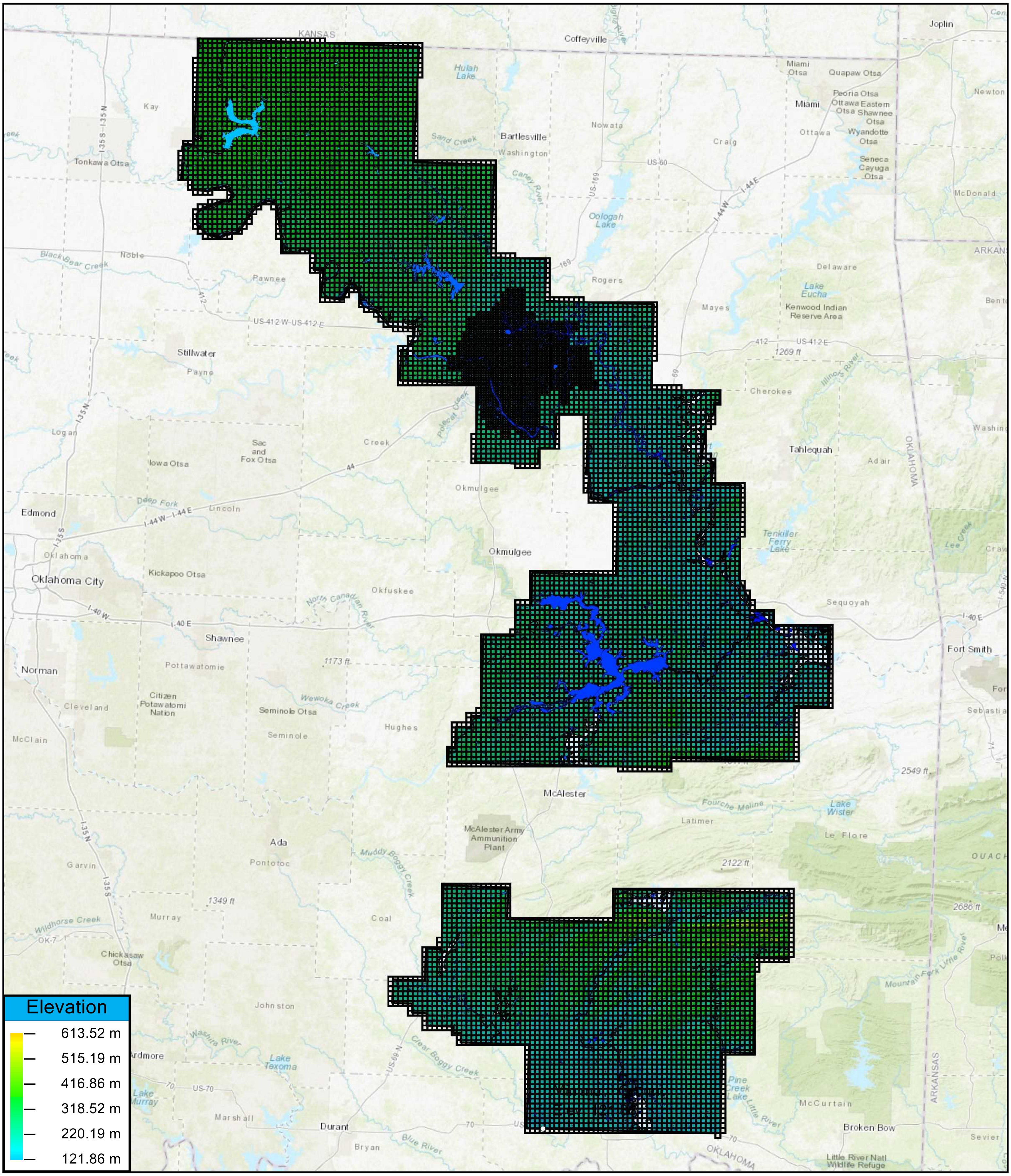
Shaded Relief Map

OK_Woodward_FEMA_R6_LiDAR_2016_D17
G17PD00013



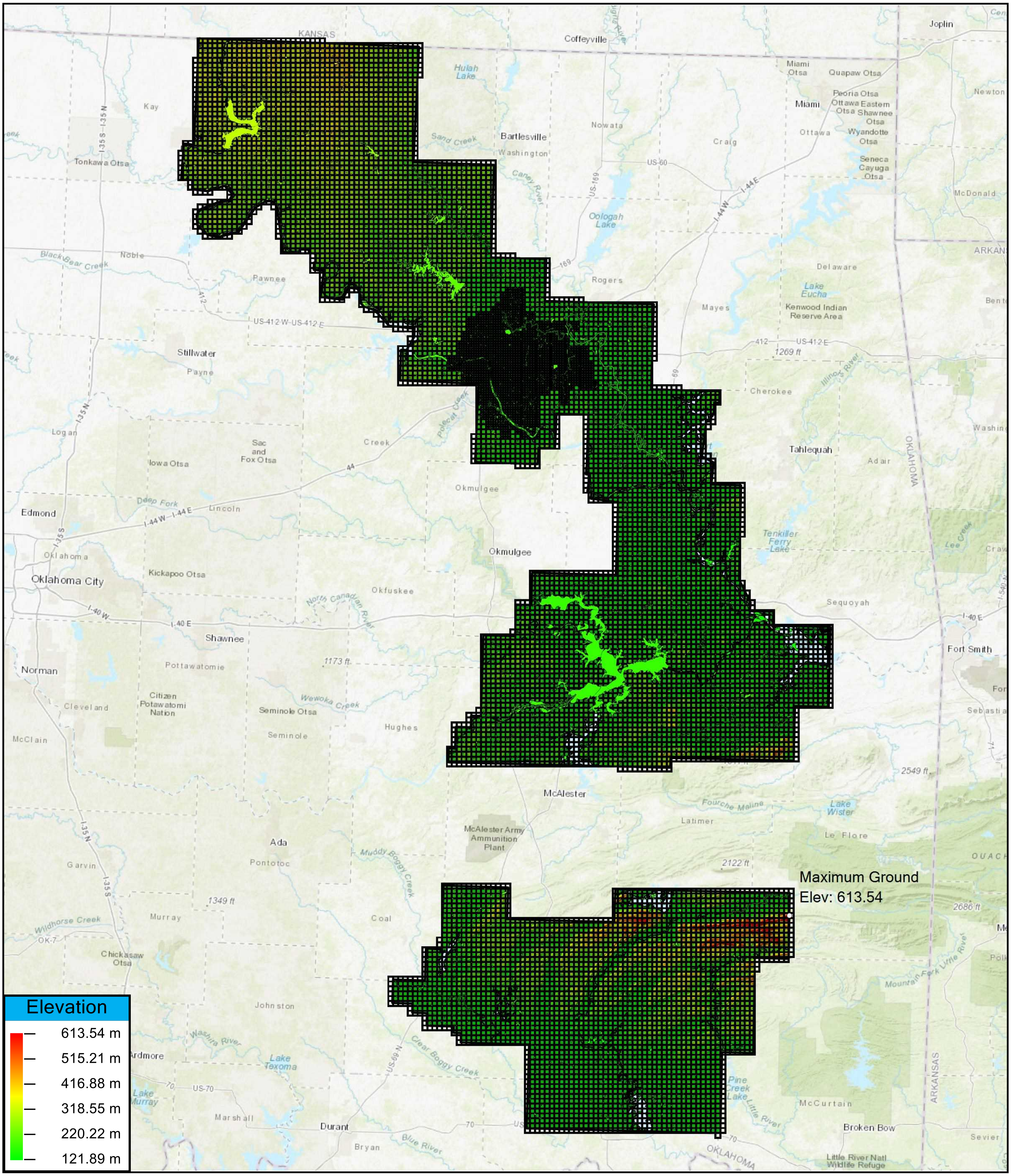
Minimum Surface Elevation

OK_Woodward_FEMA_R6_LiDAR_2016_D17
G17PD00013



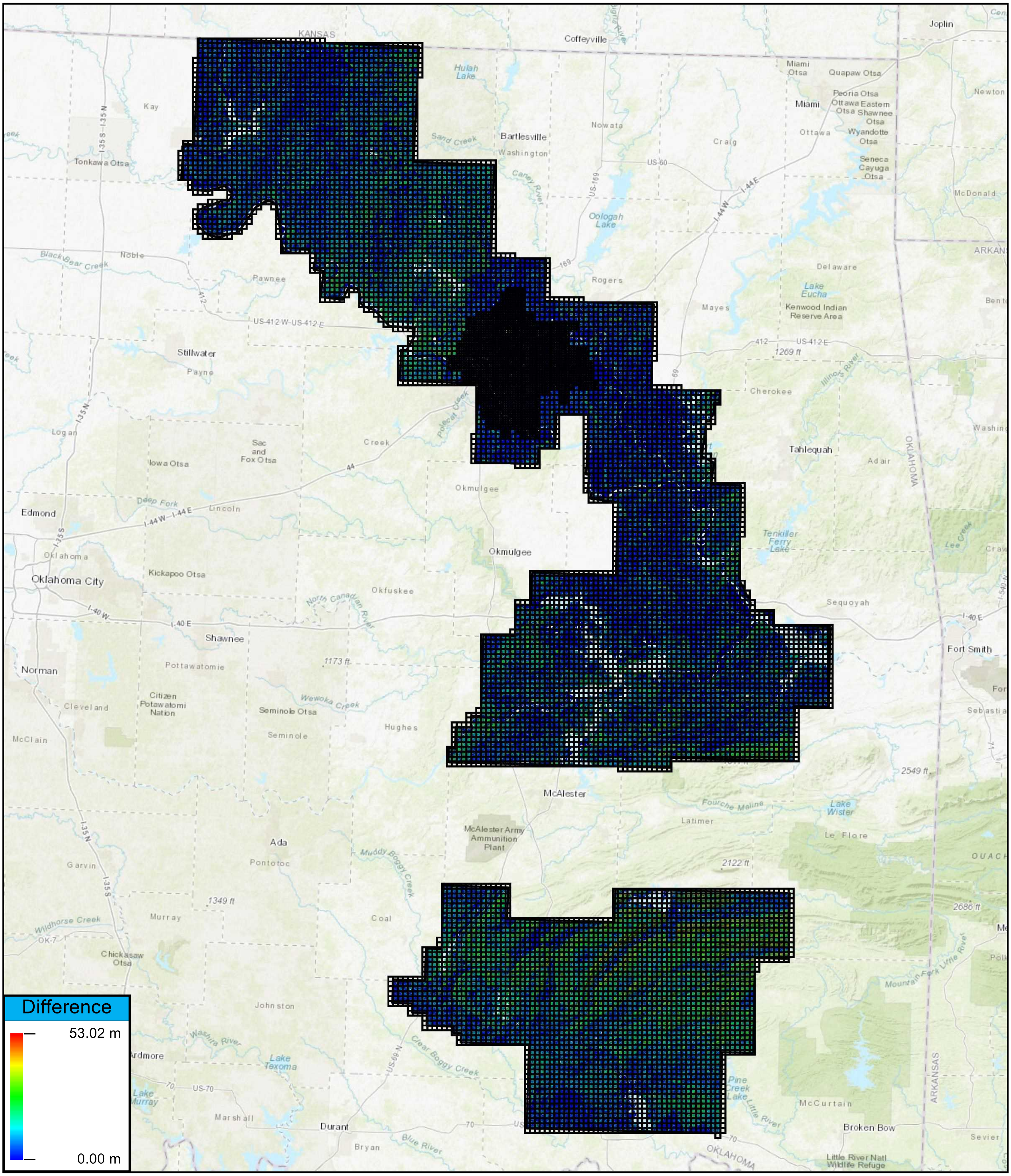
Maximum Surface Elevation

OK_Woodward_FEMA_R6_LiDAR_2016_D17
G17PD00013

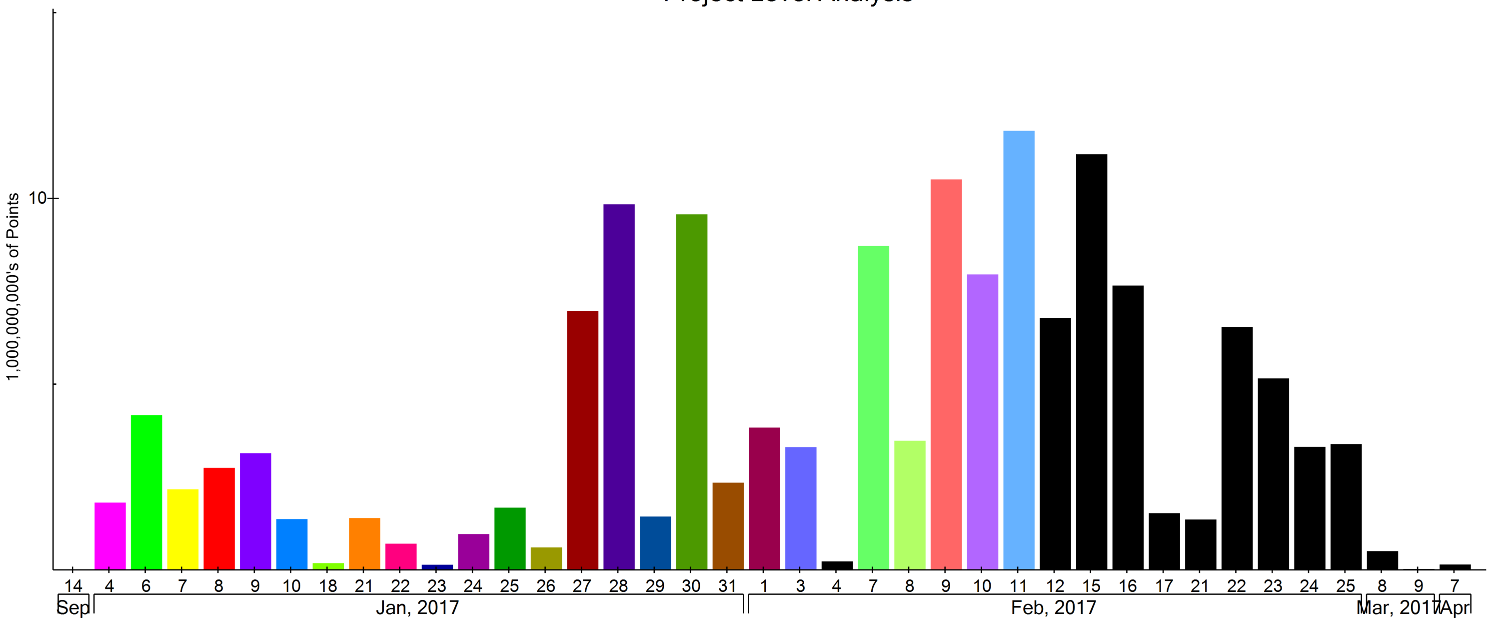


Relative Terrain Change

OK_Woodward_FEMA_R6_LiDAR_2016_D17
G17PD00013



Project Level Analysis



September, 2011

Day	Key	# of Points	% of Overall
14		1	0.0%

January, 2017

Day	Key	# of Points	% of Overall
4		1,793,947,049	1.9%
6		4,148,686,407	4.4%
7		2,152,287,500	2.3%
8		2,730,258,365	2.9%
9		3,121,371,541	3.3%
10		1,349,679,938	1.4%
18		165,098,228	0.2%
21		1,377,728,959	1.5%
22		687,536,565	0.7%
23		122,416,739	0.1%
24		946,547,128	1.0%
25		1,658,947,271	1.8%
26		586,681,084	0.6%
27		6,957,423,947	7.4%
28		9,825,130,674	10.4%
29		1,418,927,196	1.5%
30		9,555,570,779	10.1%
31		2,330,480,009	2.5%

February, 2017

Day	Key	# of Points	% of Overall
1		3,813,957,984	4.0%
3		3,287,947,072	3.5%
4		211,705,411	0.2%
7		8,704,216,252	9.2%
8		3,460,234,860	3.7%
9		10,495,480,596	11.1%
10		7,936,973,748	8.4%
11		11,802,881,256	12.5%
12		6,759,603,063	7.2%
15		11,172,313,898	11.9%
16		7,637,801,923	8.1%
17		1,509,992,314	1.6%
21		1,339,137,056	1.4%
22		6,518,135,885	6.9%
23		5,137,396,351	5.5%
24		3,295,362,212	3.5%
25		3,369,150,448	3.6%

March, 2017

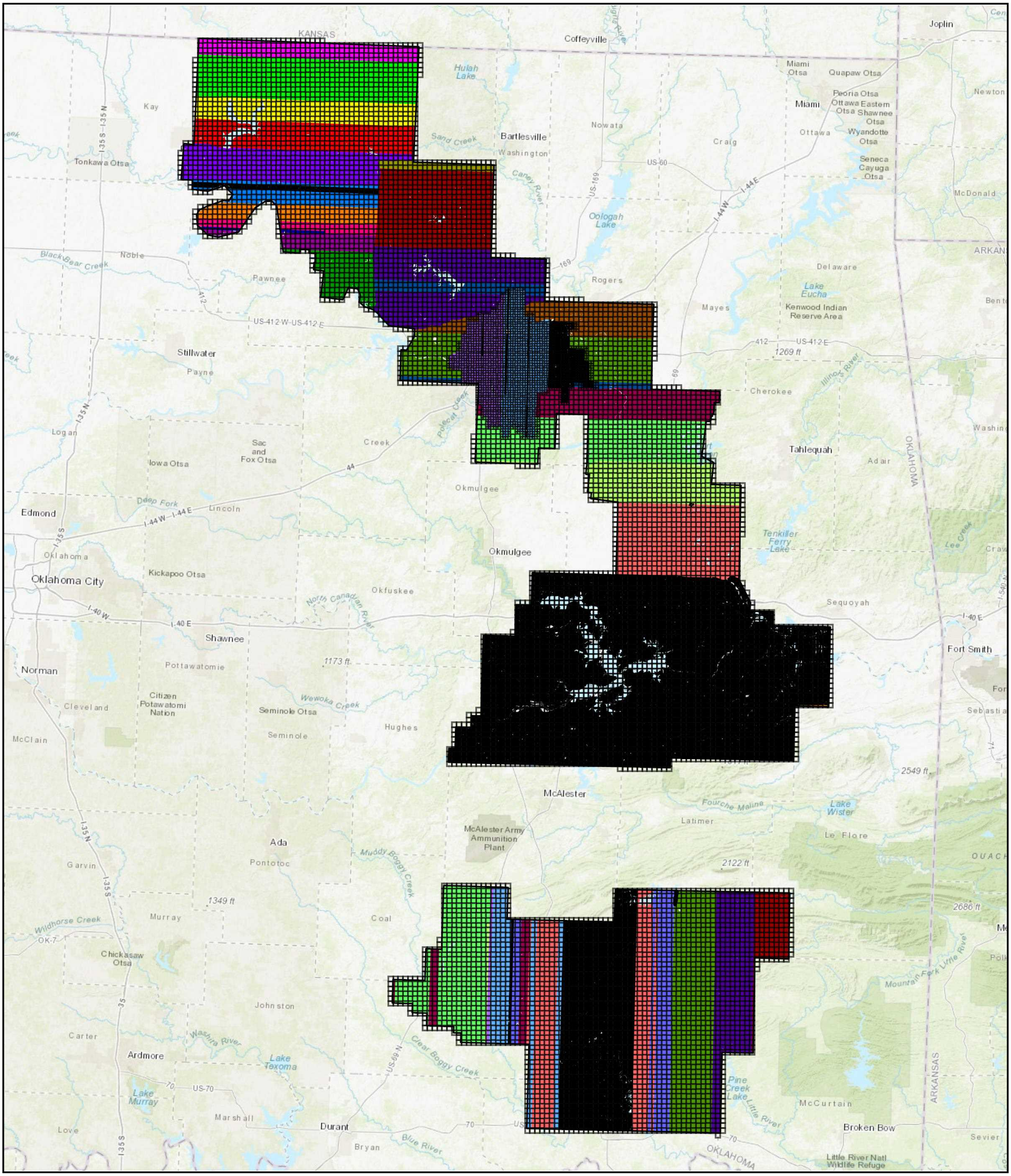
Day	Key	# of Points	% of Overall
8		488,876,116	0.5%
9		8,241,454	0.0%

April, 2017

Day	Key	# of Points	% of Overall
7		128,899,114	0.1%

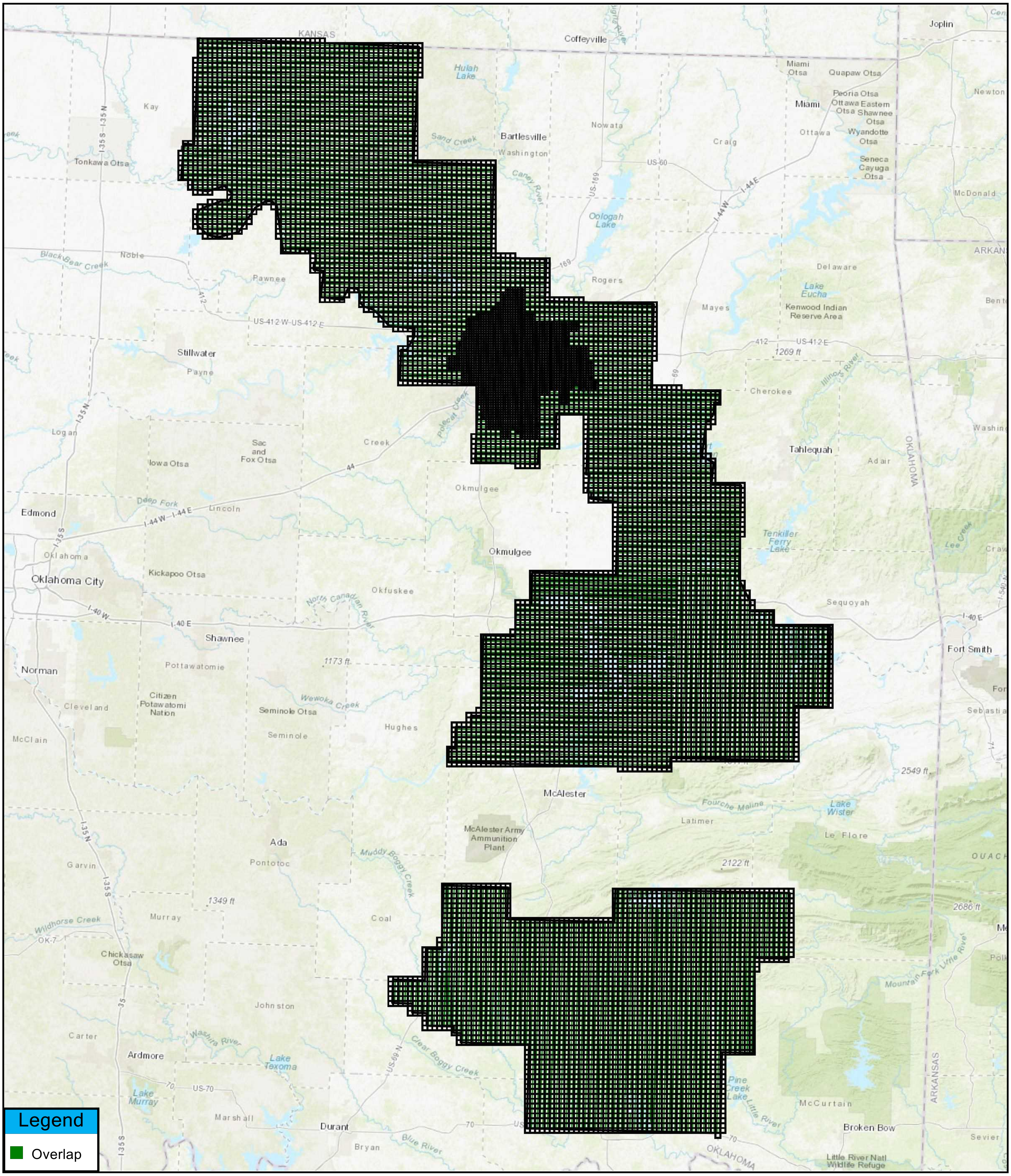
Collection Date Map

OK_Woodward_FEMA_R6_LiDAR_2016_D17
G17PD00013



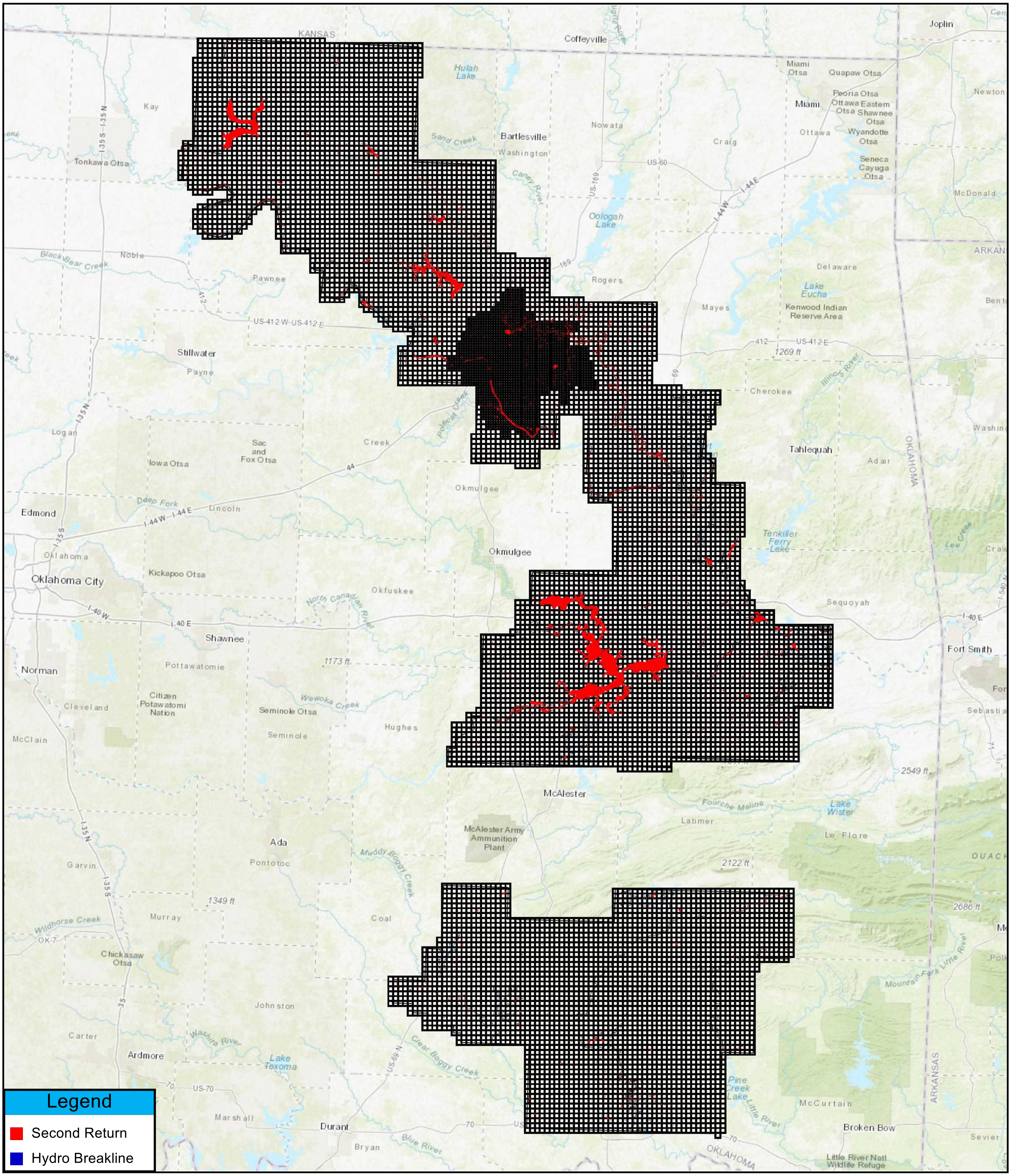
Overlap Map

OK_Woodward_FEMA_R6_LiDAR_2016_D17
G17PD00013



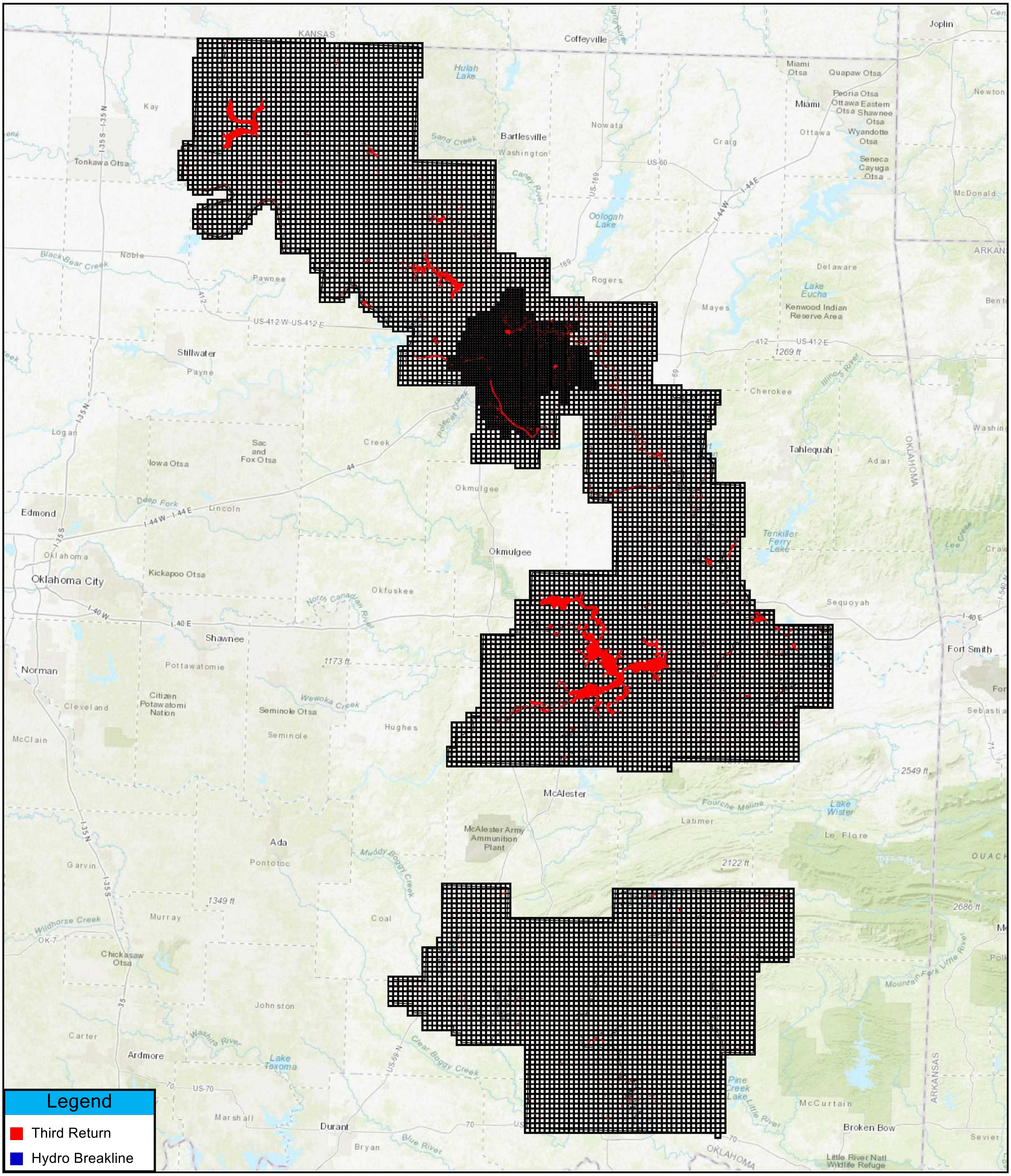
Second Return Locations

OK_Woodward_FEMA_R6_LiDAR_2016_D17
G17PD00013



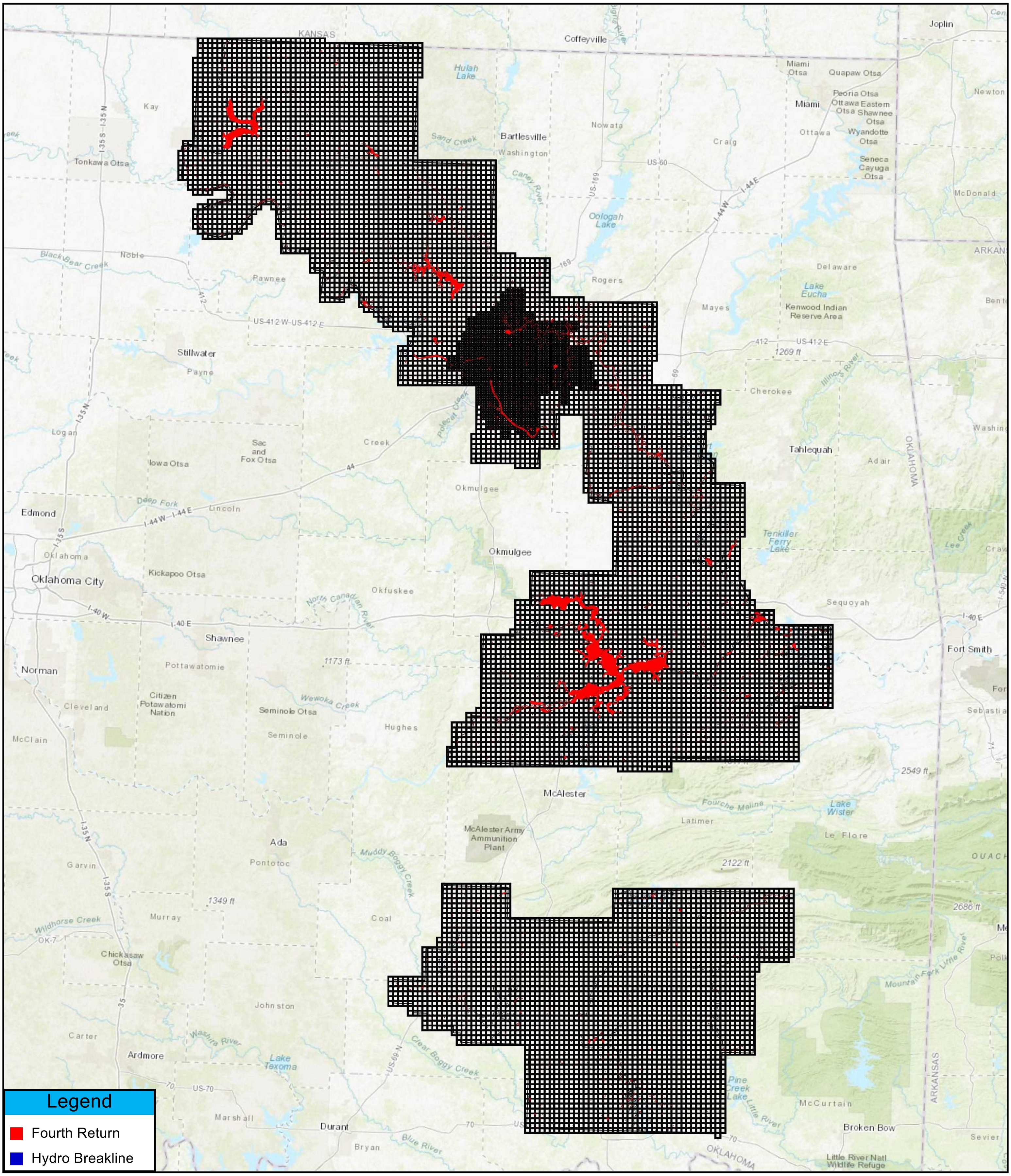
Third Return Locations

OK_Woodward_FEMA_R6_LiDAR_2016_D17
G17PD00013



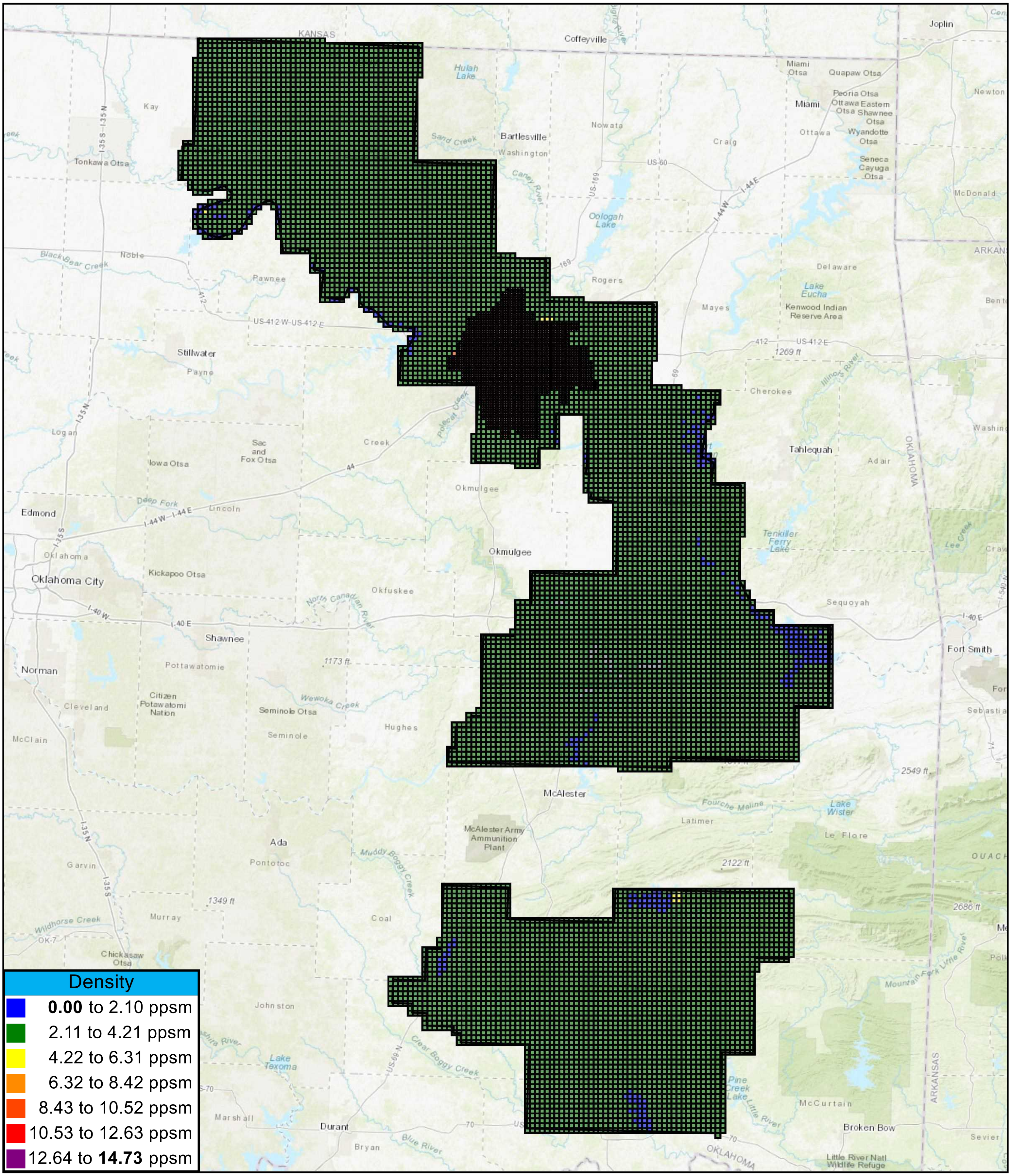
Fourth Return Locations

OK_Woodward_FEMA_R6_LiDAR_2016_D17
G17PD00013



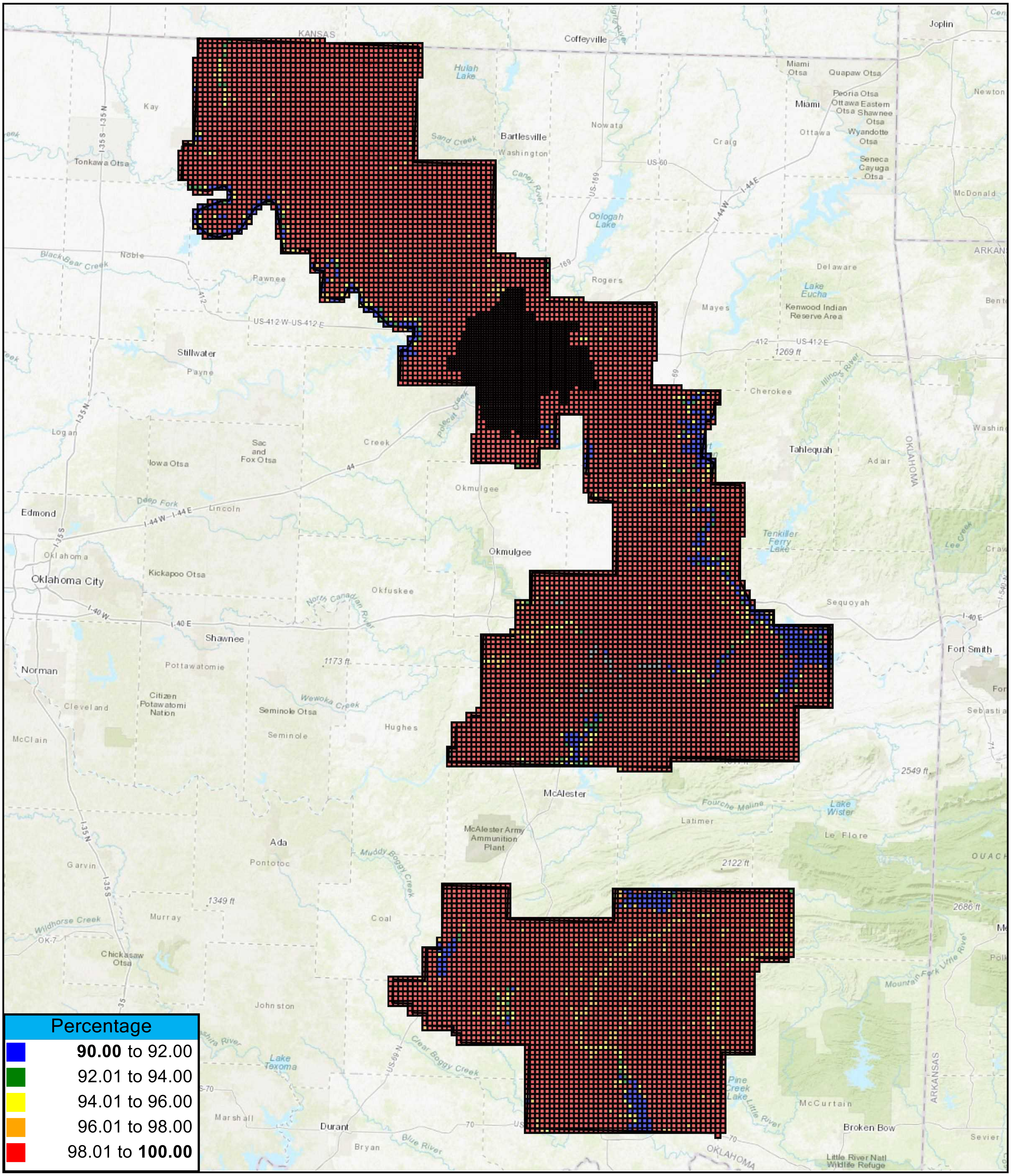
First Return Point Density

OK_Woodward_FEMA_R6_LiDAR_2016_D17
G17PD00013



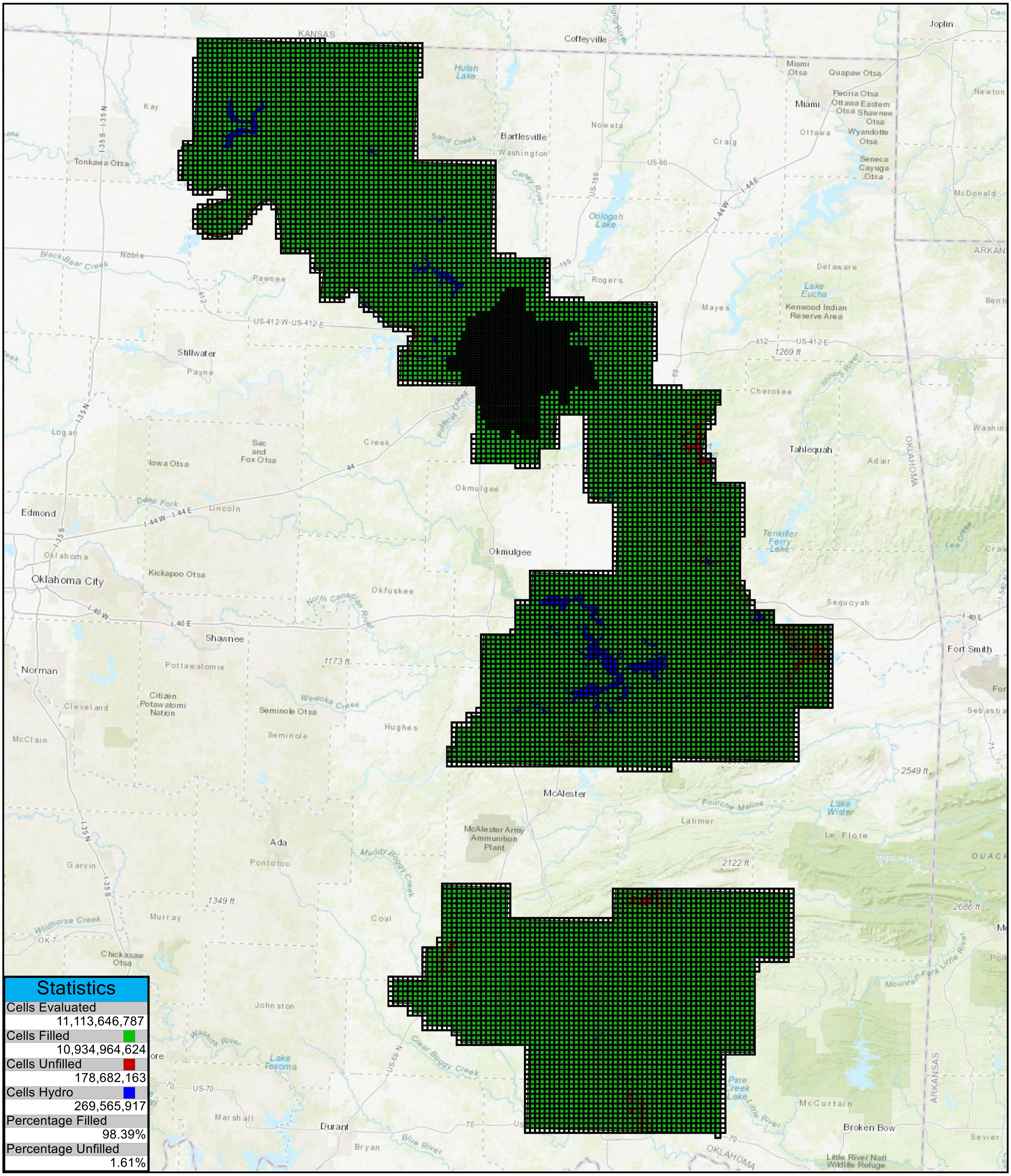
First Return Spatial Distribution Test

OK_Woodward_FEMA_R6_LiDAR_2016_D17
G17PD00013



First Return Voids At NPS*2

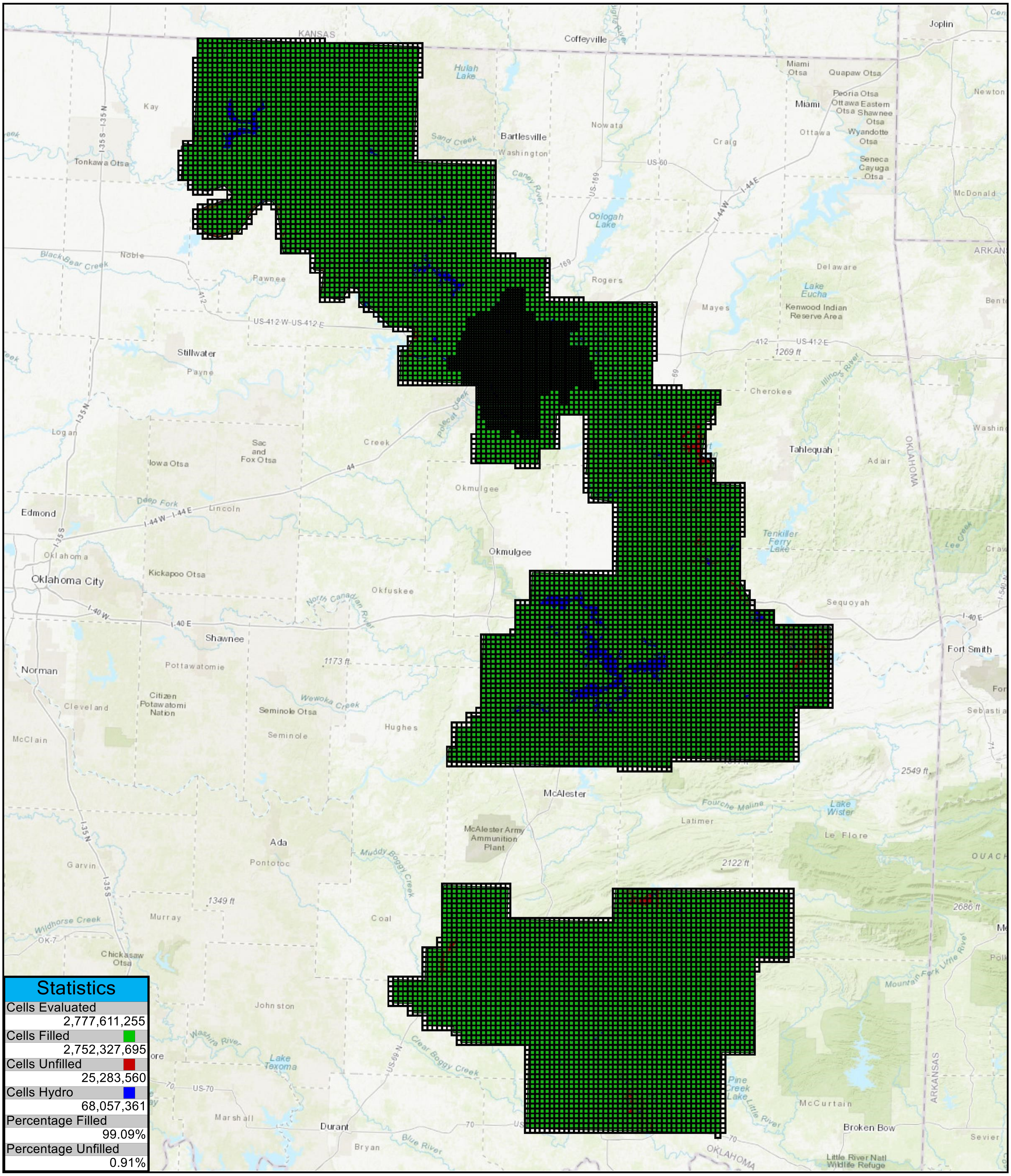
OK_Woodward_FEMA_R6_LiDAR_2016_D17
G17PD00013



Statistics	
Cells Evaluated	11,113,646,787
Cells Filled	10,934,964,624
Cells Unfilled	178,682,163
Cells Hydro	269,565,917
Percentage Filled	98.39%
Percentage Unfilled	1.61%

First Return Voids At NPS*4

OK_Woodward_FEMA_R6_LiDAR_2016_D17
G17PD00013

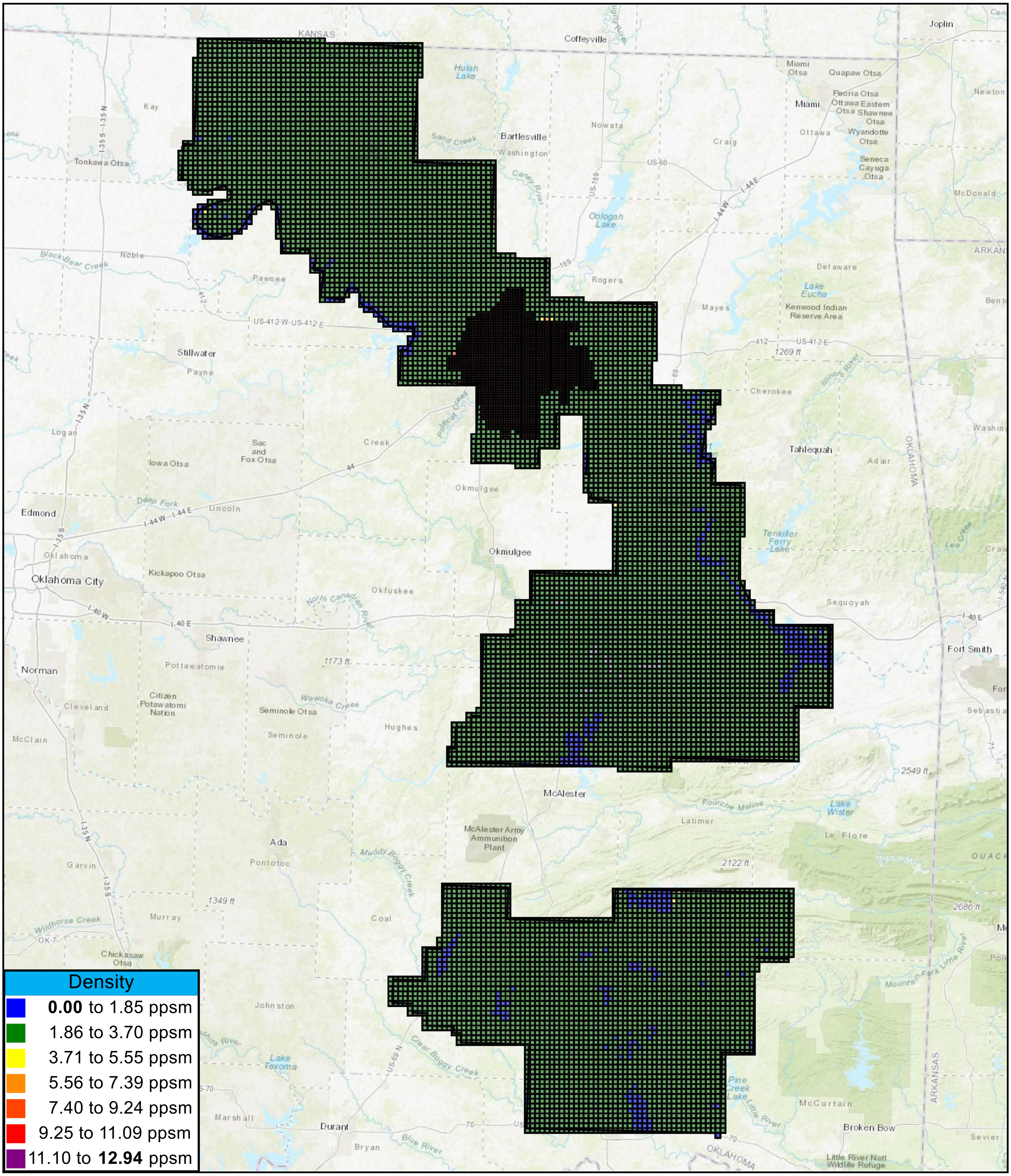


Statistics	
Cells Evaluated	2,777,611,255
Cells Filled	2,752,327,695
Cells Unfilled	25,283,560
Cells Hydro	68,057,361
Percentage Filled	99.09%
Percentage Unfilled	0.91%

quantum SPATIAL

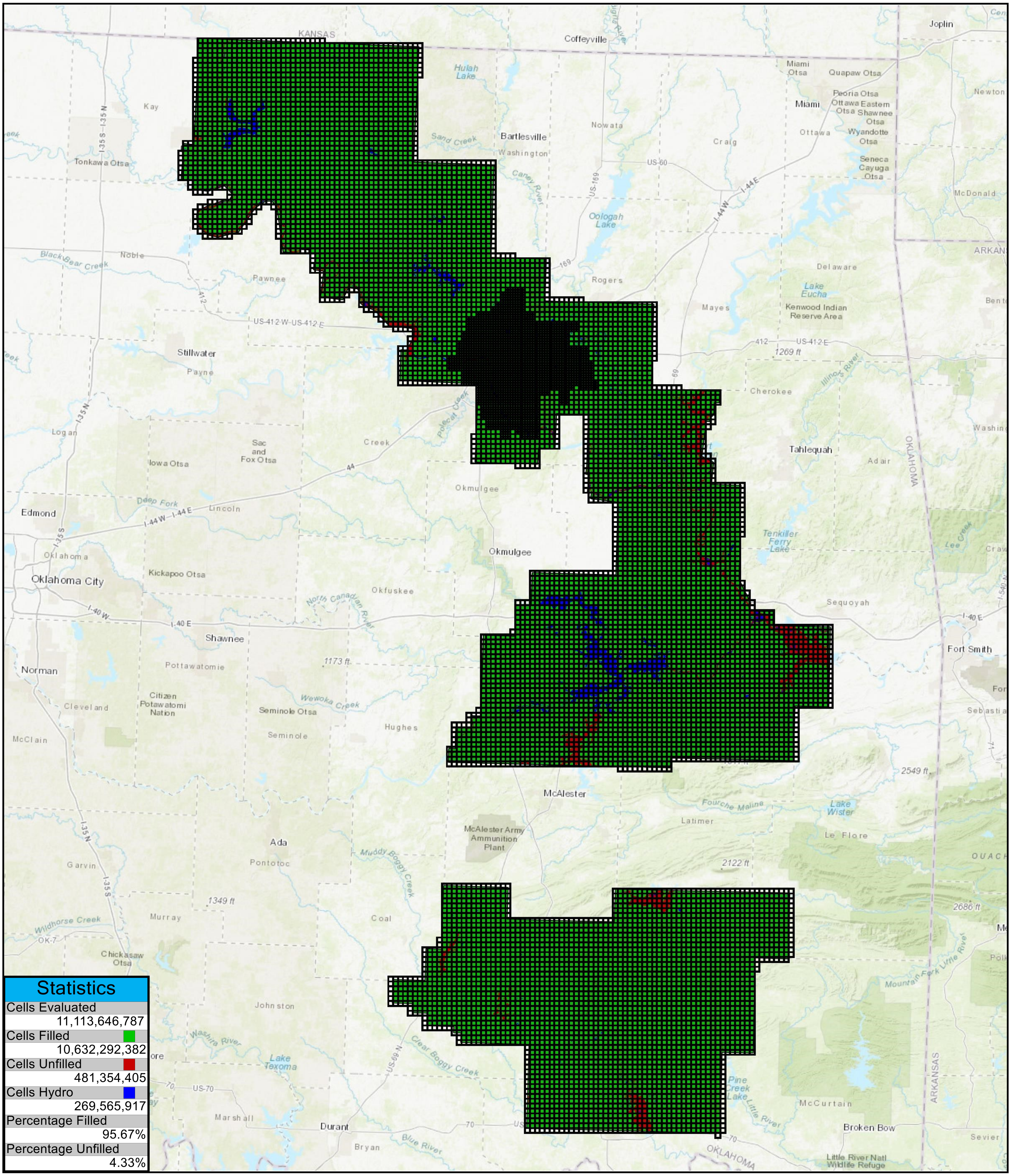
Bare Earth Point Density

OK_Woodward_FEMA_R6_LiDAR_2016_D17
G17PD00013



Bare Earth Voids At NPS*2

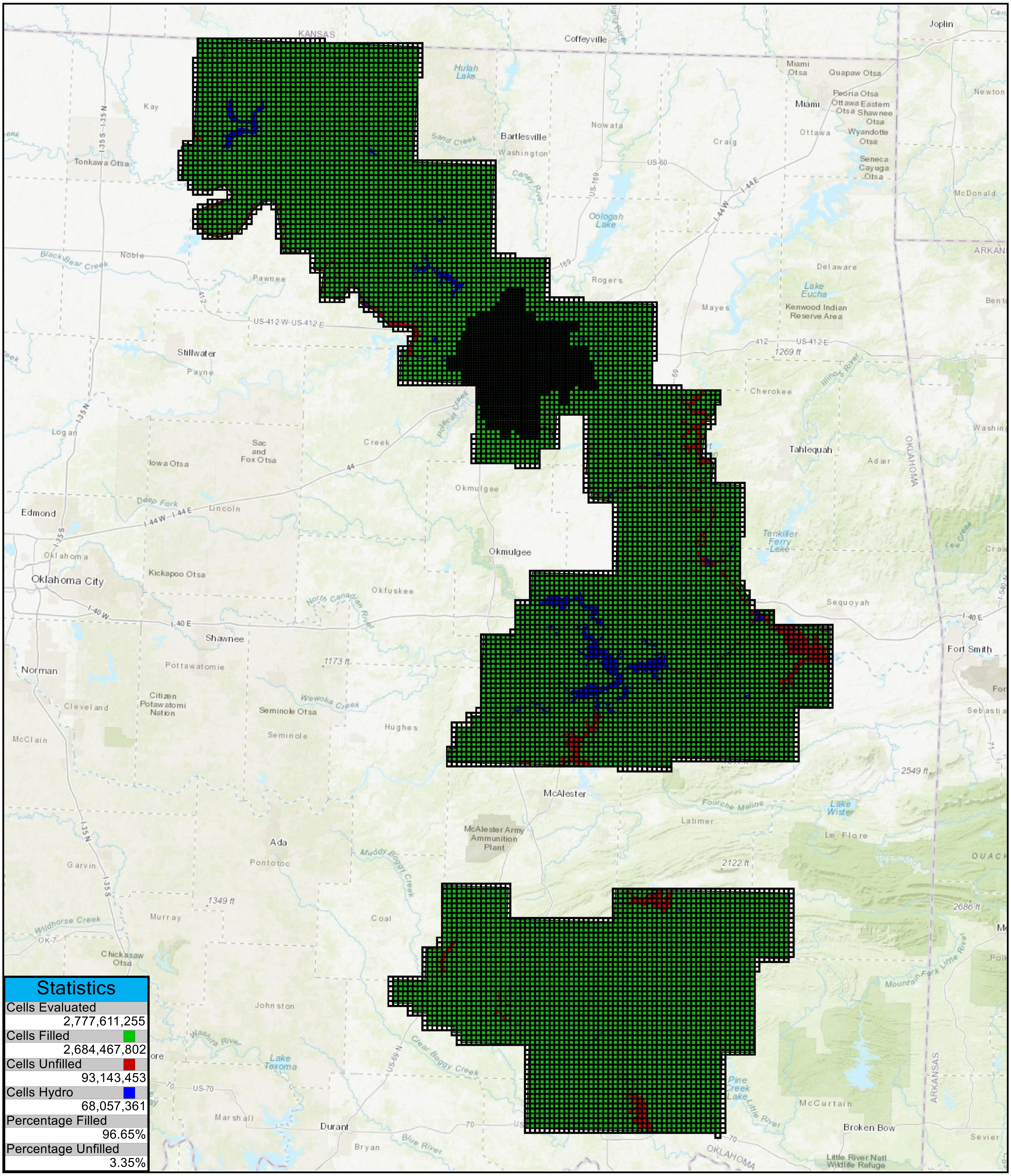
OK_Woodward_FEMA_R6_LiDAR_2016_D17
G17PD00013



Statistics	
Cells Evaluated	11,113,646,787
Cells Filled	10,632,292,382
Cells Unfilled	481,354,405
Cells Hydro	269,565,917
Percentage Filled	95.67%
Percentage Unfilled	4.33%

Bare Earth Voids At NPS*4

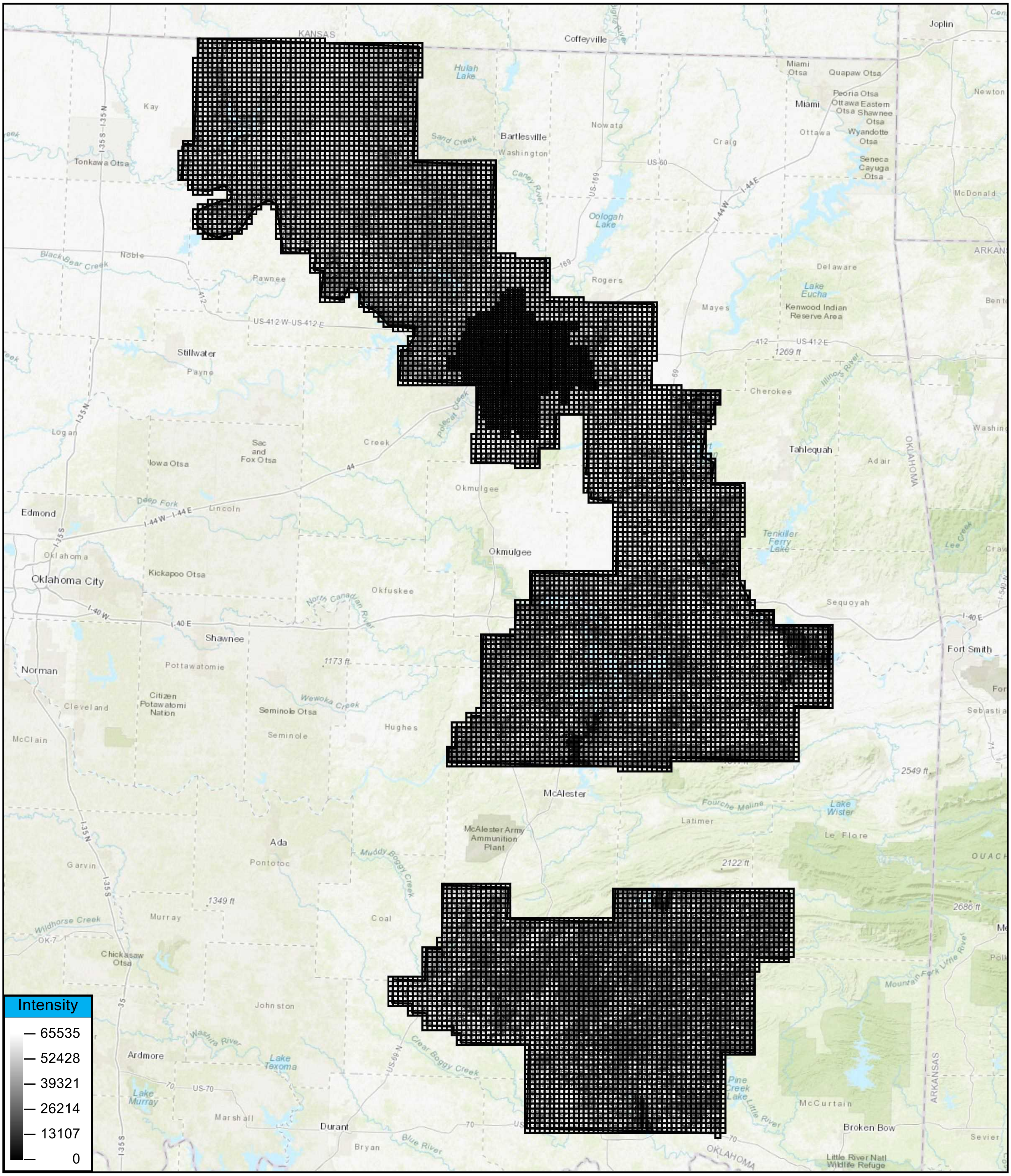
OK_Woodward_FEMA_R6_LiDAR_2016_D17
G17PD00013

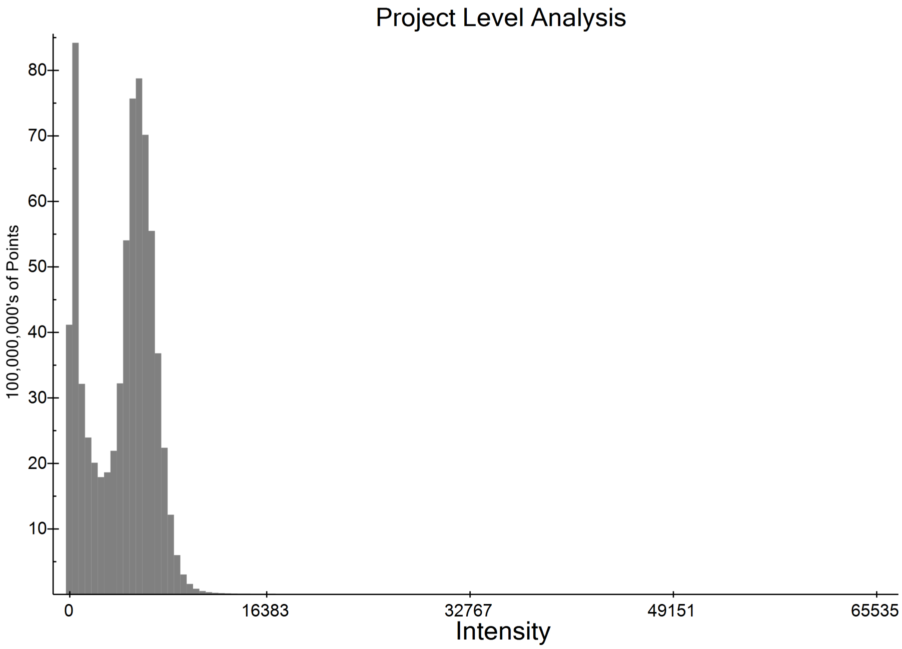


Statistics	
Cells Evaluated	2,777,611,255
Cells Filled	2,684,467,802
Cells Unfilled	93,143,453
Cells Hydro	68,057,361
Percentage Filled	96.65%
Percentage Unfilled	3.35%

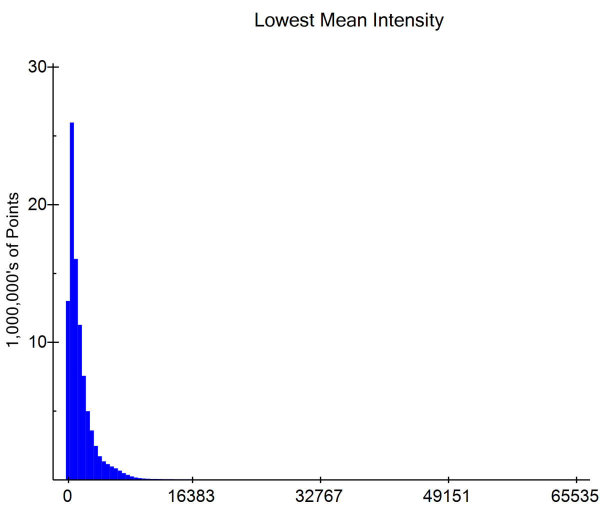
Intensity Map

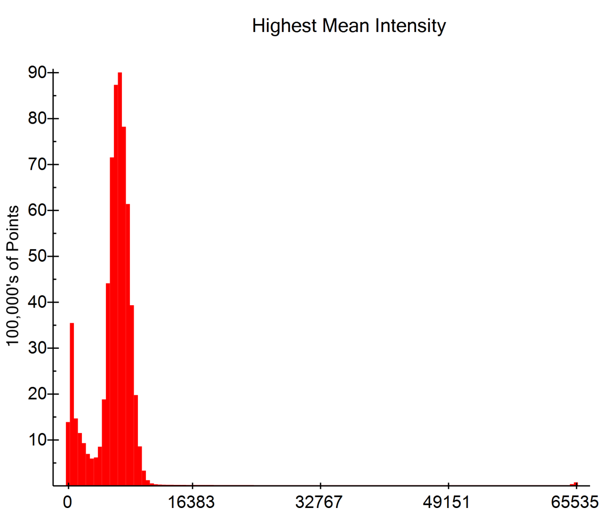
OK_Woodward_FEMA_R6_LiDAR_2016_D17
G17PD00013

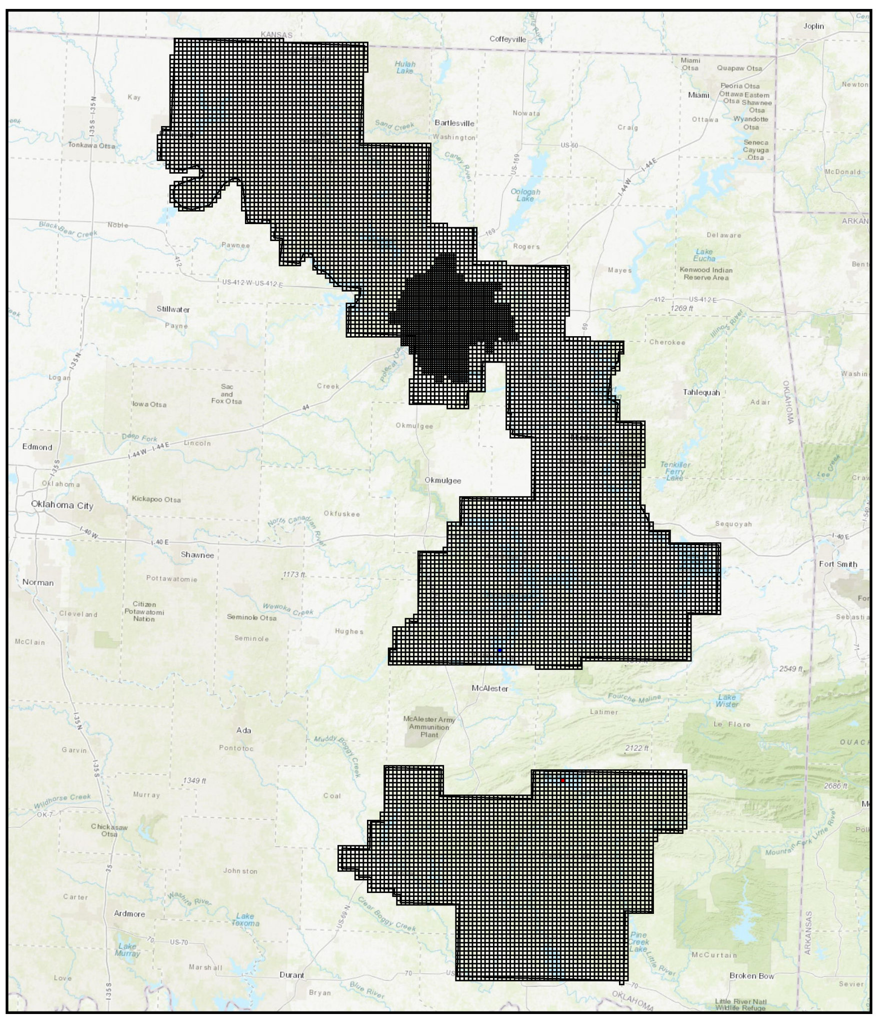


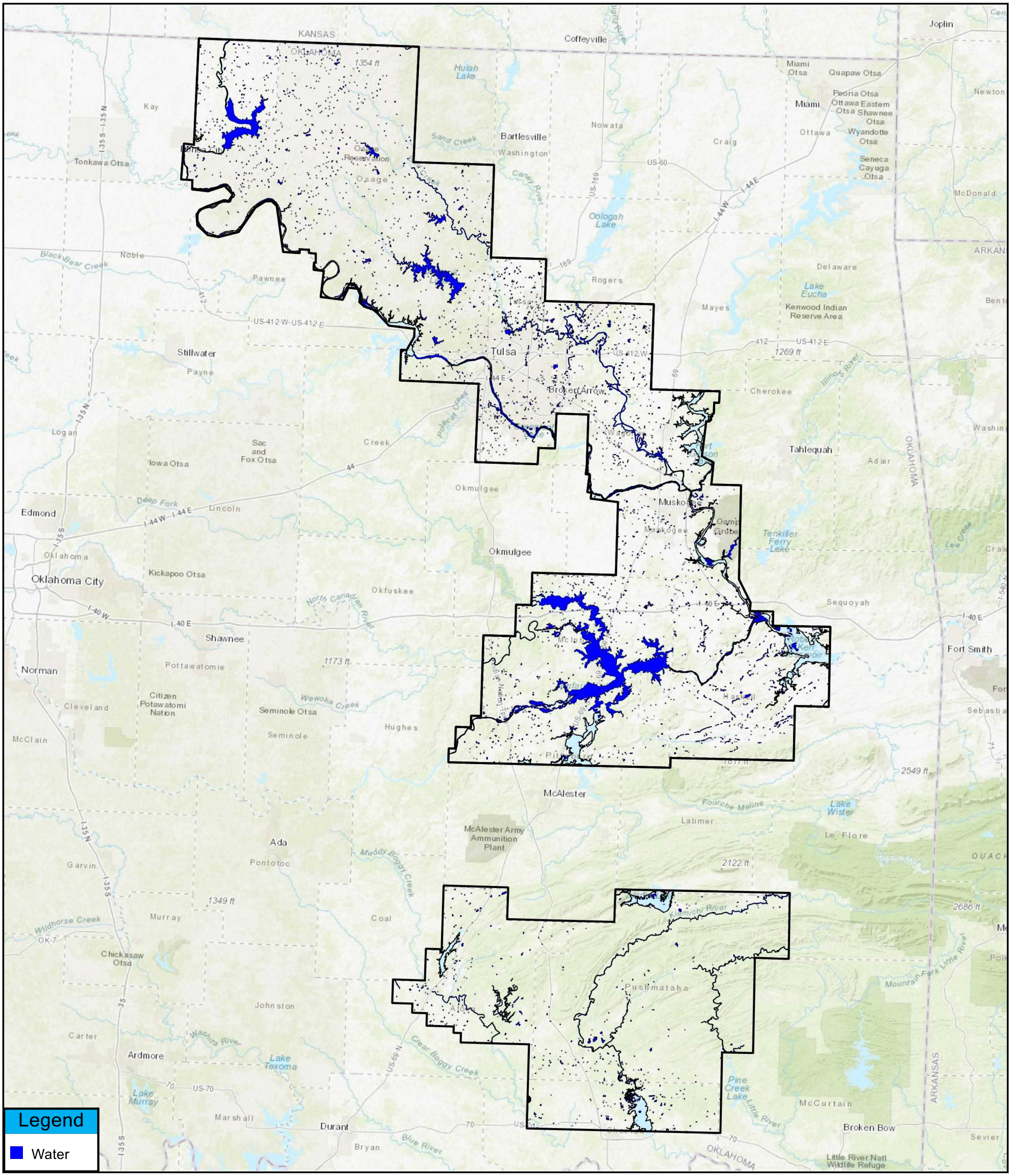


Statistics	
Project Mean Intensity	4,496.2
Lowest Mean Intensity	763.0
Highest Mean Intensity	37,287.7

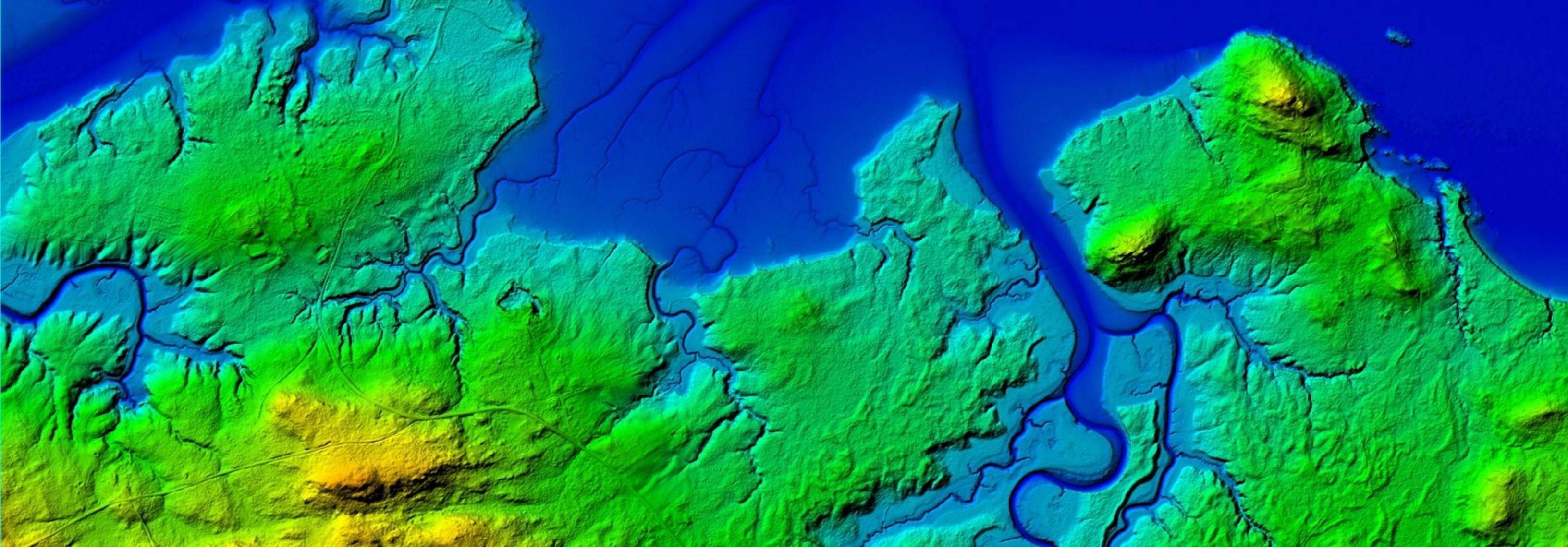








Legend
Water
KANSAS
OKLAHOMA
Coffeyville
Joplin
Hulah Lake
Miami
Quapaw Otsa
Peoria Otsa
Ottawa Eastern
Otsa Shawnee Otsa
Wyandotte Otsa
Seneca Cayuga Otsa
Kay
Bartlesville
Washington
Nowata
Craig
Tonkawa Otsa
Osage Reservation
Osage
Oologah Lake
McDonald
Noble
Pawnee
Rogers
Delaware
Lake Eucha
Kenwood Indian Reserve Area
Mayes
Stillwater
Payne
Tulsa
Broken Arrow
Cherokee
Logan
Sac and Fox Otsa
Creek
Iowa Otsa
Tahlequah
Adair
Okmulgee
Lincoln
Edmond
Muskogee
Tenkiller Ferry Lake
Oklahoma
Oklahoma City
Kickapoo Otsa
Okfuskee
Sequoyah
Shawnee
Fort Smith
Pottawatomie
Norman
Citizen Potawatomi Nation
Cleveland
Seminole Otsa
Seminole
Hughes
McClain
McAlester
Latimer
Lake Wister
Le Flore
McAlester Army Ammunition Plant
Ada
Pontotoc
Garvin
Murray
Coal
Chickasaw Otsa
Pushmataha
Johnston
Carter
Ardmore
Lake Texoma
Lake Murray
Marshall
Durant
Bryan
Pine Creek Lake
McCurtain
Broken Bow
Sevier
Little River Natl Wildlife Refuge
ARKANSAS
OKLAHOMA

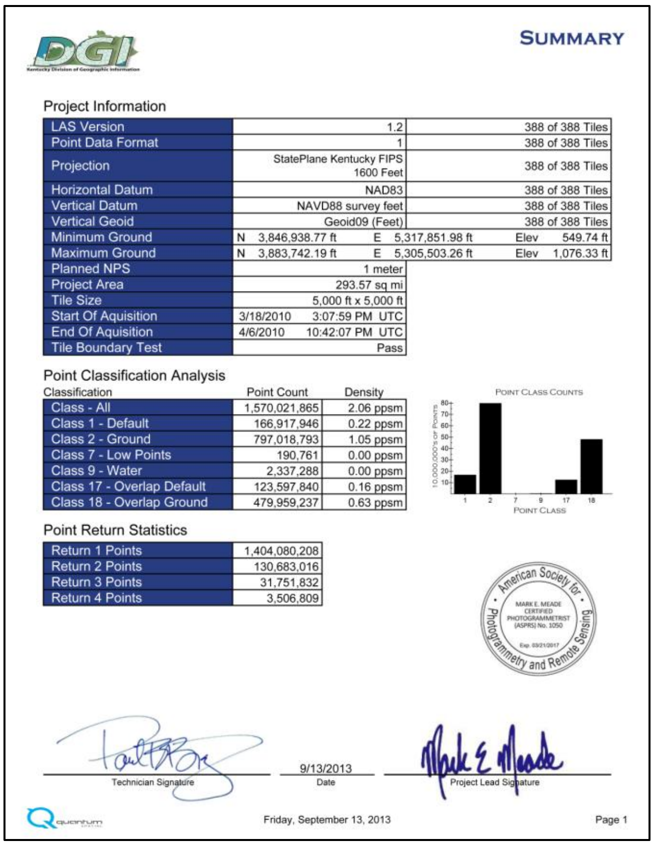


Appendix A – Explanation of Reporting

The following section provides a summary of all the reporting provided within FOCUS™. While most of the reports should be intuitive, it will be very useful to read through the background information for each of these reports to gain a full understanding of the comprehensive nature of this important tool.

Project Summary

Each of the LAS headers is carefully reviewed and a summary of this information is provided at the beginning of the report. This summary includes information for the LAS versioning, point data format, units, projection, geoid model, datums, etc. This provides a quick overall view of the project. You would normally expect that all tiles would have identical versions, point data formats, units, geoid models, projections, and datums. There are times, however, when the projection information could be different for varying groups of tiles. This might occur, for example, when a large project splits two state plane or UTM coordinate zones. Regardless, these statistics provide a quick sanity check of



SUMMARY

Project Information

LAS Version	1.2	388 of 388 Tiles
Point Data Format	1	388 of 388 Tiles
Projection	StatePlane Kentucky FIPS 1600 Feet	388 of 388 Tiles
Horizontal Datum	NAD83	388 of 388 Tiles
Vertical Datum	NAVD88 survey feet	388 of 388 Tiles
Vertical Geoid	Geoid09 (Feet)	388 of 388 Tiles
Minimum Ground	N 3,846,938.77 ft E 5,317,851.98 ft	Elev 549.74 ft
Maximum Ground	N 3,883,742.19 ft E 5,305,503.26 ft	Elev 1,076.33 ft
Planned NPS	1 meter	
Project Area	293.57 sq mi	
Tile Size	5,000 ft x 5,000 ft	
Start Of Aquisition	3/18/2010 3:07:59 PM UTC	
End Of Aquisition	4/6/2010 10:42:07 PM UTC	
Tile Boundary Test	Pass	

Point Classification Analysis

Classification	Point Count	Density
Class - All	1,570,021,865	2.06 ppsm
Class 1 - Default	166,917,946	0.22 ppsm
Class 2 - Ground	797,018,793	1.05 ppsm
Class 7 - Low Points	190,761	0.00 ppsm
Class 9 - Water	2,337,288	0.00 ppsm
Class 17 - Overlap Default	123,597,840	0.16 ppsm
Class 18 - Overlap Ground	479,959,237	0.63 ppsm

Point Return Statistics

Return 1 Points	1,404,080,208
Return 2 Points	130,683,016
Return 3 Points	31,751,832
Return 4 Points	3,506,809

American Society for Photogrammetry and Remote Sensing — MARK E. MEADE CERTIFIED PHOTOGRAMMETRIST (ASPRS) No. 1050

Technician Signature — 9/13/2013 Date — Project Lead Signature

Friday, September 13, 2013 — Page 1

all tiles in the delivery. A quick test is also performed to verify that all points within a tile fit within the exact boundary of the tile. This is shown as the tile boundary test and is presented in terms of a pass/fail. If any points for an individual tile are found outside of the logical tile boundary, an exception log is created that includes the tile name and the horizontal location and vertical position of all exceptions within that tile.

The summary also provides detailed information for the classification for all LiDAR returns, including a histogram that summarizes this analysis. This provides a very good check on the accuracy of the point classification and would serve to highlight missing or invalid classes. For example, if a single point was incorrectly identified as Class 29 (with no expectation of such a class in the project specifications), it will show up in this summary. Finally the summary page provides a detailed look at the number of 1st, 2nd, 3rd, and 4th returns in the acquisition. This can be very useful to idenitify a sensor malfunction that results in the failure to record multiple returns, or possibly an acquisition with unusually high or low numbers for multiple returns.

First Return Density Analysis

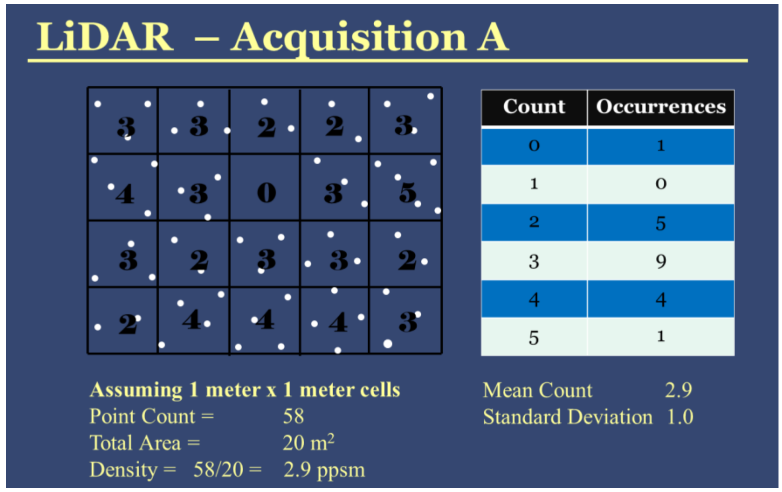
Our first return density analysis takes the review of the spatial distribution of the LiDAR returns to a level never achieved before. The ideal acquisition (at least for most projects) would be a perfectly uniform and square grid of laser returns that are spaced evenly throughout the entire project with equal along- and cross-track dimensions. This "ideal" condition is not perfectly achievable in the real world due to turbulence, cross winds (that result in aircraft crab), varying terrain elevations, the scan characteristics of the various LiDAR sensors, changing wind speeds, and many other factors.

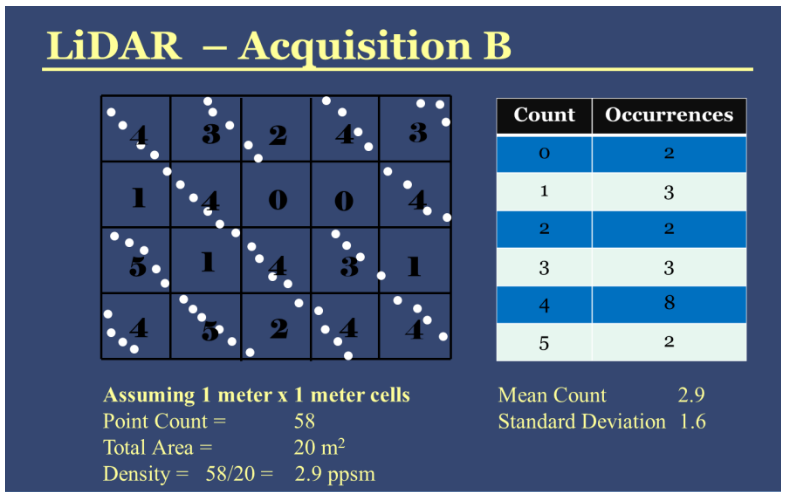
The most simplistic way of reporting the nominal point density is to derive a count of the number of first returns within the overall project and divide that total by the overall project area. While this is technically a correct way to determine the average or nominal point density, it doesn't really tell the whole story.

Instead of this more simplistic analysis, we use a series of three grids to better analyze the density of first return points and to perform tests analagous to the spatial distribution and void tests as defined by the US Geological Survey (USGS) LiDAR Base Specification Version 1.0[1]. The first analysis uses a grid overlaid on the entire project area with a cell size of 1 meter by 1 meter. Once the grid is overlaid, we simply look into

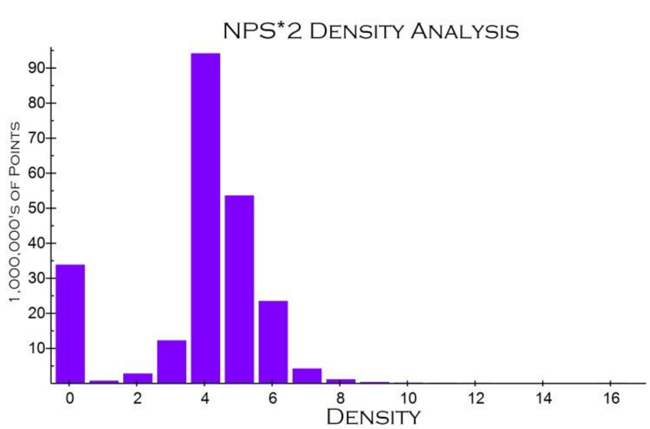
[1] Heidemann, Hans Karl, 2012, Lidar base specification version 1.0, U.S. Geological Survey Techniques and Methods, book 11, chap. B4, 63p.

each cell and count the number of first returns within each cell. We then develop a histogram of the results and determine the average and standard deviation for the overall project. We then repeat this same test two more times with a grid of cells measuring the project's Nominal Post Spacing (NPS) x 2, and the NPS x 4. The NPS x 2 was chosen as this is the basis of a clustering, or spatial distribution test within the USGS LiDAR specifications. The NPS x 4 was chosen as this is the basis of a void test for these same specifications.



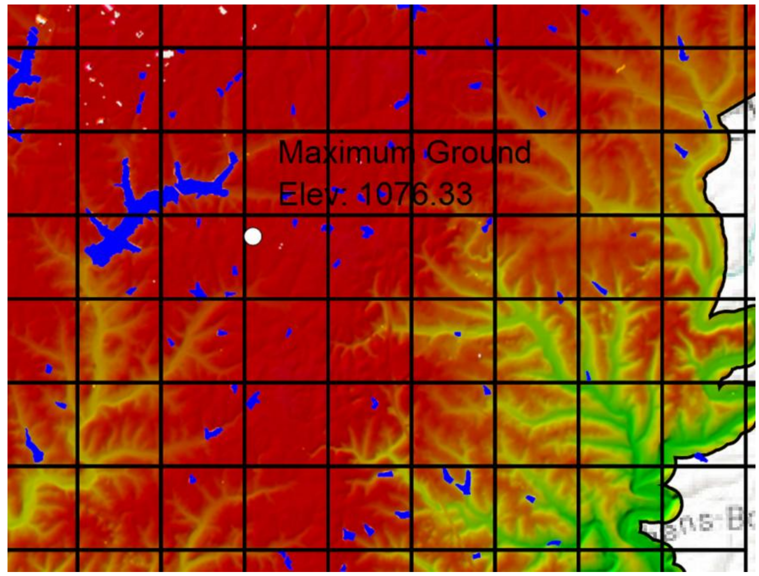


The two graphics at right illustrate this point. It should be apparent that the flight direction is in a northeast – southwest direction. In Acquisition A, the along- and cross-track point spacing is fairly consistent, indicating an effective flight plan. In Acquistion B, the cross track point spacing is much tighter (nominally about a 4 to 1 ratio) than the along track spacing, which would be undersirable 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.



2 Meter Cell (NPS*2)			
Average	3.85	Standard Dev.	1.90
Return Count	# of Cells	Return Count	# of Cells
0	33,759,123	9	266,273
1	663,996	10	98,439
2	2,688,201	11	45,350
3	12,158,911	12	29,267
4	94,065,088	13	15,167
5	53,516,159	14	9,656
6	23,379,551	15	5,986
7	4,117,316	16+	32,597
8	1,030,492		

Shaded Relief Map



Our shaded relief map is generated from each of the actual tiles on the delivery media. It is useful to get an overall view of the project area along with the terrain captured by the LiDAR acquisition. The shaded relief is draped over the tile layout and project boundary (when available). This graphic provides a quick visual check for missing or corrupt tiles (missing or corrupt tiles will not be shaded and therefore appear as a void area within the graphic), and can also illustrate large data gaps within individual tiles. The location of the minimum and maximum points within the ground class are also located on this graphic.

Minimum Surface Elevation

This graphic depicts the minimum elevation within the ground class for each of the tiles in the delivery. The ground class is defined as Class 2 and when present, Class 8 (present when the model key class is part of the project requirements). In producing this graphic, each tile is subdivided into 50 rows and 50 columns and the minimum elevation within each of these sub grids is rendered. This graphic is very useful for making a quick determination of unusually low points or other elevation anomalies.

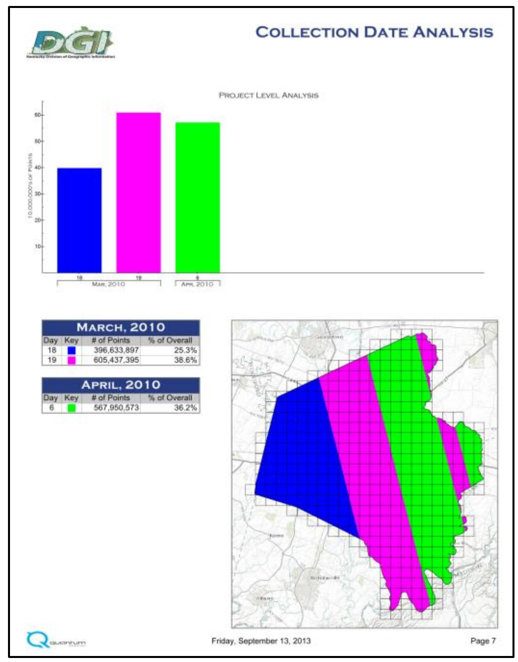
Maximum Surface Elevation

This graphic depicts the maximum elevation within the ground class for each of the tiles in the delivery. As with the minimum elevation graphic described above, the ground class is defined as Class 2 and Class 8, when present. As with the minimum elevation graphic detailed above, when producing this graphic each tile is further subdivided into 50 rows and 50 columns and the maximum elevation within each of these sub grids is rendered. This graphic is very useful for making a quick determination of unusually high points or other elevation anomalies.

Relative Terrain Change

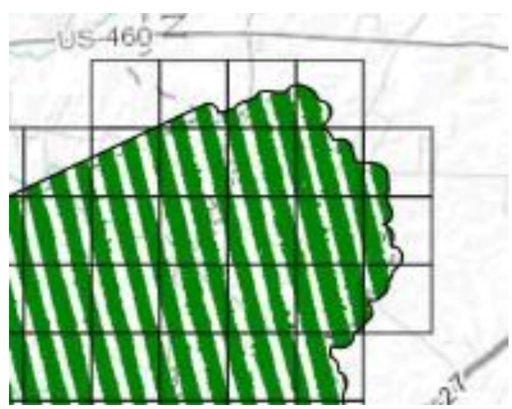
The relative terrain change graphic is representative of the amount of elevation change within each of the sub grids (50 rows by 50 columns for each tile) within the project area. This elevation difference between the maximum and minimum ground surface elevations discussed above is determined and rendered within the graphic. Relatively flat areas will exhibit very little difference between the minimum and maximum surface elevations. Conversely, steep areas will exhibit fairly substantial differences between these surface elevations.

Collection Date Analysis



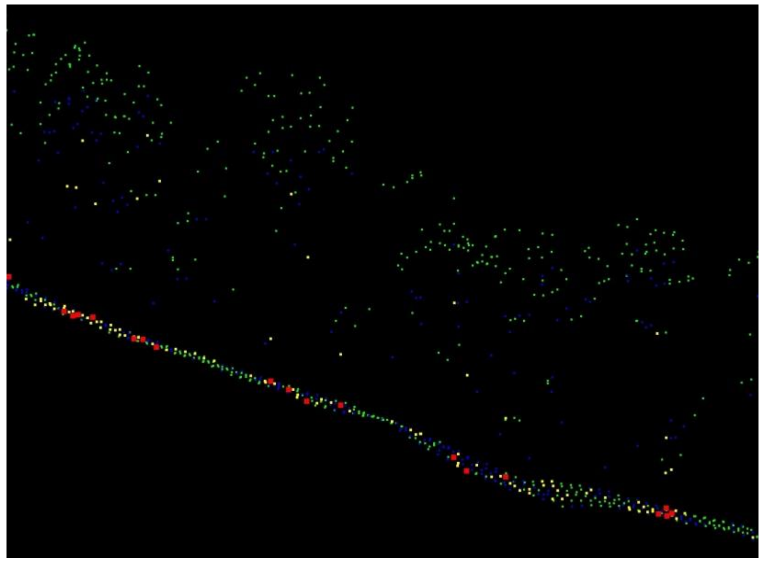
This graphic provides useful information relating to the way the LiDAR point cloud data was acquired. The graphic is rendered by collection date based on UTC time. Multiple acquisition dates will be rendered with multiple colors. A statistical summary is also provided, which illustrates the LiDAR returns by flight date as a percentage of the overall number of returns within the project. This graphic is developed strictly from the GPS time tags in the LAS file structure, and as such provides an accurate representation of the final composition of the acquisition dates that would discard all lines that might have been reflown due to issues in the acquisition.

Overlap Map



The overlap map provides a graphic illustration of the side overlap between adjacent parallel flight lines. For this graphic, all points within the side overlap zone are rendered in green, and are overlaid on a location map of the project area. The ideal situation is to have perfectly parallel overlap zones that are also very consistent in width. There a number of factors, however, that can have significant effects on the consistency of the overlap throughout parallel flight lines. Significant changes in terrain elevations, turbulence that can affect the roll of the aircraft during acquisition, the pilot's ability to follow pre-planned flight paths at consistent altitudes, and sensor performance will all result in variation within this overlap.

Second, Third, and Fourth Return Locations

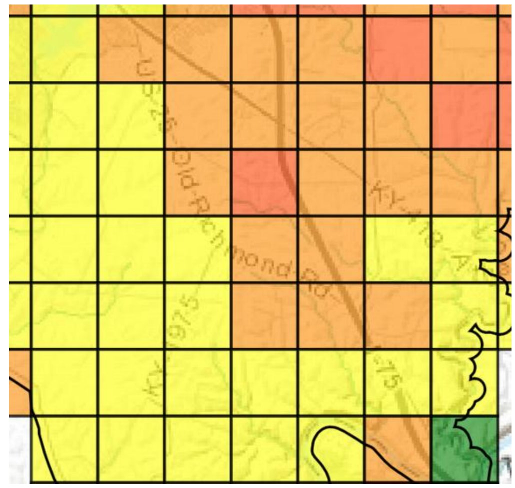


Similar to the graphic above, we provide detailed information for the location of all second, third, and fourth returns within the project area. These graphics are somewhat different, however, as they are derived from the relative density of these returns within a grid of 50 rows and 50 columns within each tile. Basically we derived a count of the number of second, third, and fourth returns within each of these cells and then render the project area based on these densities. Cells with a very low density of these multiple returns will appear transparent. Cells with high densities will be rendered as darker colors.

Note that the graphic for the fourth returns will be a subset of the other two graphics as you can't have a fourth return without a second and third. Similar logic applies to the third return graphic related to the second return graphic. The analysis of the third and fourth return locations will typically provide a very good idea of the presence of relatively tall vegetation. This is because today's high end discrete return LiDAR sensors have a minimum pulse discrimination distance ranging from about 0.75 to 3 meters. This means that the sensor cannot record a second return within this discrimination range from the first return (and the same argument applies to the third from the second, and fourth from the third). Therefore you won't get any fourth returns unless the distance from the first to the fourth is nominally three times the pulse discrimination distance, or more. In the case of a sensor with a discrimination of 1.5 meters, the first return must be at least 4.5 meters (or about 15 feet) higher than the fourth.

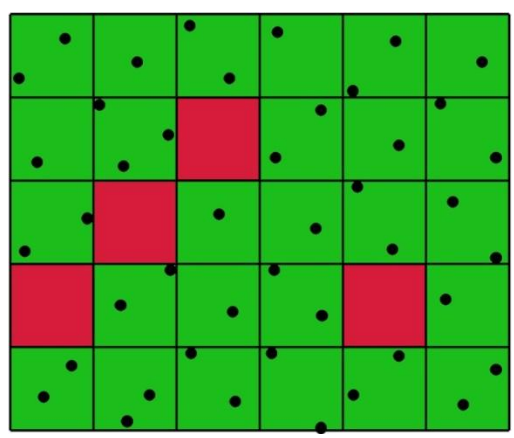
The graphic on the previous page illustrates multiple returns in tall trees. In this case the trees are about 110 feet in height. The green returns are first, blue second, yellow third, and red fourth (last) returns.

First Return Density Map



This graphic depicts the point density of first returns for each of the tiles in the delivery. This density is determined by dividing the total number of returns within a tile, using classes 1-6, 8-10, and 13-15, by the area of the tile. This value is expressed in the units of points per square meter (ppsm) regardless of the units selected (feet or meters) for the project. Multiple returns from a single outgoing pulse are not considered in this determination. This density will be negatively affected by water or other very low reflective surfaces (e.g., fresh asphalt). If the project boundary splits any tile, the calculation takes place only within the project boundary. Translucent colors are used in this graphic so that you can see the project map behind the rendering. This can be useful in evaluating tiles with lower first return point densities that might be affected by water bodies that are often visible in the background project map.

First Return Spatial Distribution Test



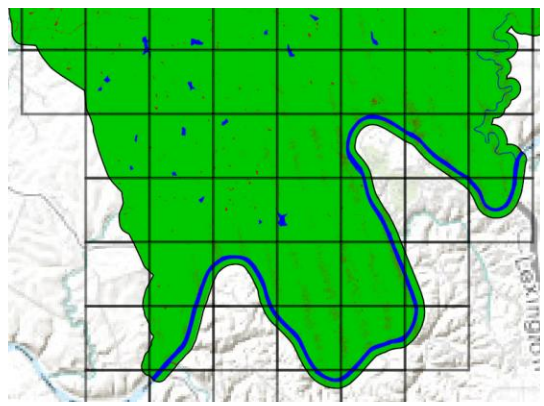
This graphic provides the results of a spatial distribution, or clustering, test as required by the USGS LiDAR Base Specification. A uniform grid is overlaid on the LiDAR returns (first returns). This is a square grid with linear dimensions along the sides of the grid equal to the NPS x 2.0. For example, a project with a NPS of 0.7 meters would result in a grid of 1.4 meters on each side. Each grid cell within the project boundary is examined to determine if there are any returns that fall within that grid cell as indicated in the graphic at right. If at least one return falls within a cell then that cell is counted as a populated cell. If not, that cell is counted as one void of returns. If hydro breaklines were collected for the project then any cell that either touches a hydro breakline, or falls entirely within a hydro breakline is removed from the test.

The USGS specification requires at least 90% of the tested cells to 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 for this rendering.

The results of this test will be skewed (negatively) 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).

First Return Voids at NPS x 2 and NPS x 4

These two graphics and legends provide additional information from the spatial distribution test discussed in the section before this one. The only difference between these two tests is the cell size of the grid overlaid on the first return points. One is based on the NPS x 2, while the second is based on the NPS x 4. The latter is considered to be "voids" within the data.

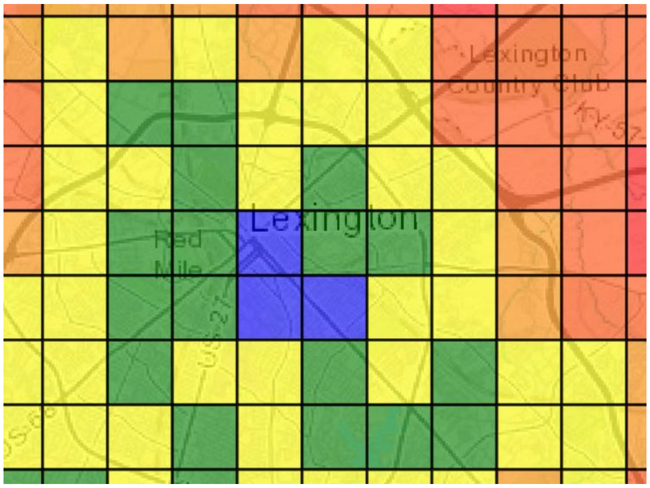


The USGS specification defines data voids within a single swath as unacceptable, except when caused by water bodies, areas of low near infra-red reflectivity such as asphalt or composition roofing, or where filled in by another swath. It is extremely rare for this void test to result in no voids within 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 hydro bodies, or in fresh asphalt surfaces.

All individual unfilled cells are illustrated within this graphic by the color red overlaid on a green background. The hydro breaklines are shown in blue. This provides a very clear understanding of the location, density, and grouping of any void areas. The legend provides very clear information on the number of cells evaluated; the subset of the evaluated that are filled, unfilled, or located within hydro breaklines; and the percentage of the evaluated cells that are filled and unfilled.

Bare Earth Density

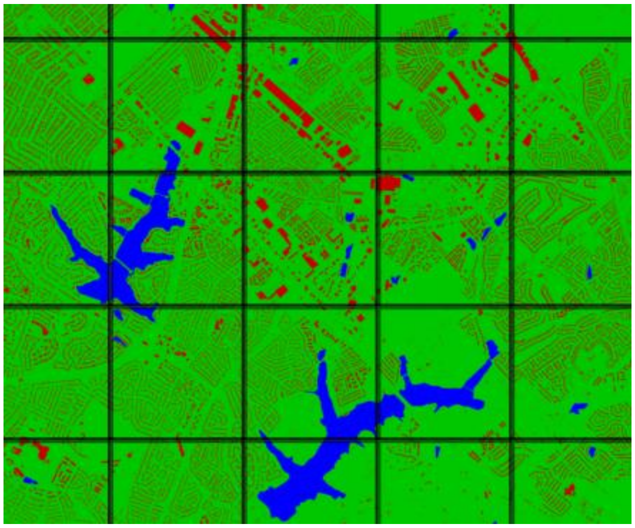
This graphic depicts the point density for each of the bare earth returns on a tile-by-tile basis in the delivery. We define bare earth as Class 2 (ground) and Class 8 (model key), if applicable. This density is determined by dividing the total number of bare earth ground returns within a tile by the area of the tile. Points classified as overlap are excluded from the density calculation.



Again, this value is always expressed in the units of ppsm. This density will also be affected by water or other very low reflective surfaces. This density can be reduced significantly by buildings, dense vegetation, bridge decks, etc. as these points are removed from the bare earth surface. Again, if the project boundary splits any tile, the calculation takes place only within the boundary. The graphic above illustrates a lower bare earth density in the urban downtown area in blue, followed by a slightly higher density in residential areas shown in green, with the highest densities surrounding these developed areas that are representative of wide open areas and horse farms.

Bare Earth Voids at NPS x 2 and NPS x 4

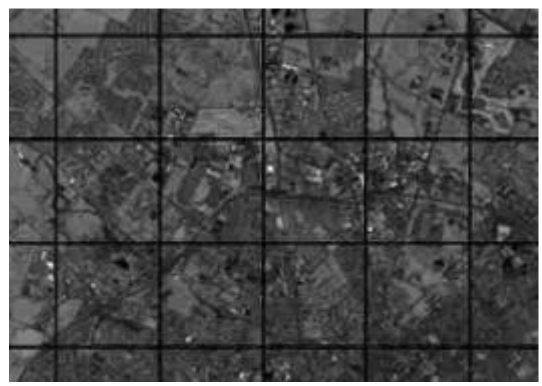
Our graphics for the bare earth voids are identical to the tests that we perform on the first return LiDAR surface with the one significant exception that these tests are performed only on the bare earth class (Class 2, and Class 8 when model key is included in the project). Some of our clients think of this as a test of the effectiveness of the laser's penetration in vegetation, and it serves as valuable tool in this respect. But this test is also significantly affected by the built environment (e.g., homes, commercial buildings, bridges, etc.) that are always removed from the bare earth class.



We perform these tests by overlaying a square grid over the project area with the dimensions along each side of the cell fixed at the NPS times two and times four. As an example, for a project designed for a NPS of 1.0 meters we would use cells of 2.0 x 2.0 meters, and 4.0 x 4.0 meters in this evaluation. We simply overlay these cells on the LiDAR surface and look to see if there is a bare earth return within each cell. If there is at least one, we render that cell green and add it to the list of populated cells. If there are no bare earth returns within the cell, then we render that cell as red and add it to the list of unpopulated cells. We then provide the rendered project area and complete summary statistics of this analysis. Note that any areas that fall within hydro breaklines are rendered as blue and are excluded from the statistical analysis.

Intensity Map

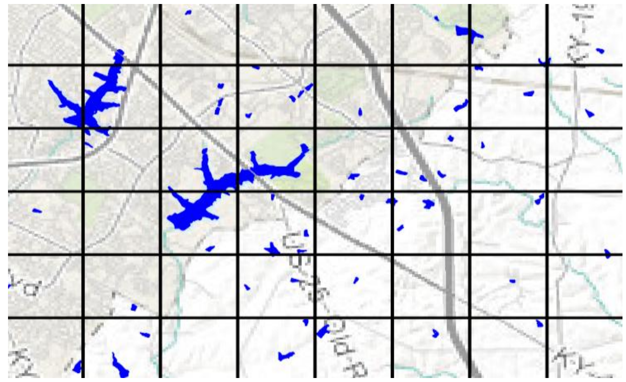
Our intensity graphic is generated from each of the actual tiles on the delivery media. It is useful to get an overall view of the project area along with the intensity captured by the LiDAR acquisition. The intensity plot is draped over the tile layout and project boundary (when available). This graphic can display potential problems with the recorded intensity values found in the LAS files.



Intensity Analysis

Today's 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. This 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. Most LiDAR units capture this intensity as an 8-bit value, which provides 256 relative values ranging from 0 to 255. We provide an overall project histogram of the first return intensities, and highlight the individual tiles with the highest and lowest mean intensities. Note that the actual intensity characteristics can vary significantly based on the project area and the sensor used for the acquisition.

Breakline Map



This graphic depicts the location of all hydro breaklines collected 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.

Calibration

The accuracy of LiDAR point clouds are affected by systematic errors or scaling. The accuracy is also affected by variable errors result from GNSS conditions that might include baseline length, number of satellites tracked, values of positional dilution of precision (PDOP), etc. During the initial processing of LiDAR data, geospatial firms typically spend a considerable amount of effort to remove both systematic and variable errors that allow the development of a homogenous elevation surface for the entire project area.

This results in quality data fitting well from flight line to flight line, and from mission to mission. This homogenous surface is then typically fit to ground through the use of calibration points located throughout the project area. This graphic depicts the results of the final calibration of this surface. All calibration points are shown as solid circles centered about their horizontal position, are scaled by the amount of relative error at each of the points (larger circles represent larger errors), and color coded by the direction of the error (whether the LiDAR surface is either higher or lower than the ground calibration point). The graphic is extremely useful to analyze the distribution of the calibration points within the project area as well as looking for systematic errors that might remain in the LiDAR surface after calibration. The statistical analysis of this final calibration is included in tabular form with this graphic.

Drive Contents

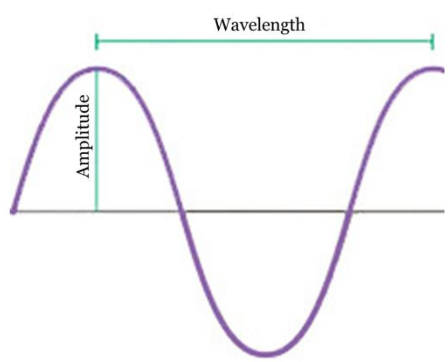
This illustration provides a quick look at the directory structure and location of all electronic files on the delivery media. All contents under the FOCUS directory are written onto the delivery media during the final checks and provide all results of these tests, including this document.

Appendix B – Glossary of LiDAR Terminology

Absolute Accuracy – The degree to which a point within the LiDAR point cloud conforms to its correct location on the earth within an accepted coordinate system. See also *Relative Accuracy*.

Accuracy –The term accuracy is often used inconsistently when describing a LiDAR elevation surface. Under NSSDA, however, the term accuracy is defined as the 95% confidence interval, which would be equivalent to the interval in which you would expect to see 95% of the errors within a LiDAR dataset. For example, if the "accuracy" of a dataset is stated as 25 cm, you should expect that 95% of random points sampled from the dataset would fall within 25 cm of their correct position.

Amplitude – In LiDAR, the 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 – Attenuation refers to 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 bare earth surface is 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.

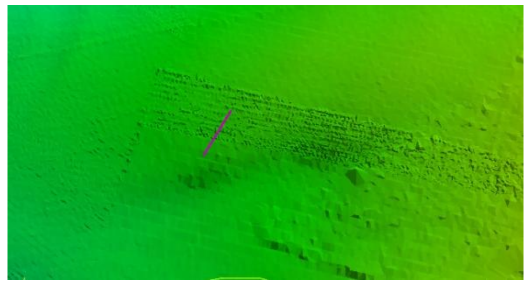
Beam Divergence – The energy emitted by the laser within a LiDAR sensor leaves the sensor as a very narrow beam of light, but increases in diameter along the path to the ground. The angle at which the beam increases is known as the beam divergence. This divergence is typically measured in the units of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

Breakline – A breakline is 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) – The CVA for a LiDAR elevation surface is defined as the accuracy of that surface in all land cover combinations. Technically 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 as shown in the graphic at right.



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 of today's top-of-the-line LiDAR sensors can measure and record 4 discrete returns per outgoing laser pulse. Typically these returns are 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 is quite similar to the NOHD, in that it represents a safe distance for laser operation. But the significant difference here is that this distance is reduced from the NOHD by the assumption that someone 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 eyesafe range. See also *Nominal Ocular Hazard Distance*.

Feature Class – A feature class is 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.

FEMA Land Cover Classes – FEMA defined standard land cover categories for testing within a LiDAR surface in their *Appendix A: Guidance for Aerial Mapping and Surveying*, which was published in April 2003. These classes include: 1) Bare earth and low grass, 2) High grass, weeds, and crops, 3) Brush lands and low trees, 4) Forested, fully covered by trees, 5) Urban areas, 6) Sawgrass, and 7) Mangrove.

Field of View (FOV) – The field of view 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 today's LiDAR sensors are typically selectable during flight planning and many sensors have a maximum full angle FOV of about 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 today's sensor range from a few decimeters, to a meter or more in diameter. You can think of this simply as the area of the ground illuminated by the non-visible laser beam emitted from the LiDAR sensor.

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 today's INSs is 200 Hz, which provides updates 200 times per second during flight.

Intensity – Today's 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. This 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 – See FEMA Land Cover Classes.

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

Laser Repetition Rate – The laser repetition rate is defined as the number of emitted pulses per second from the laser within a LiDAR sensor. This is typically specified in the units of kHz, with today's top-of-the-line sensor operating in the general maximum range of 150 to 500 kHz. This is also known as the pulse repetition frequency (PRF).

LiDAR – LiDAR is 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 in LiDAR 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. This is 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.

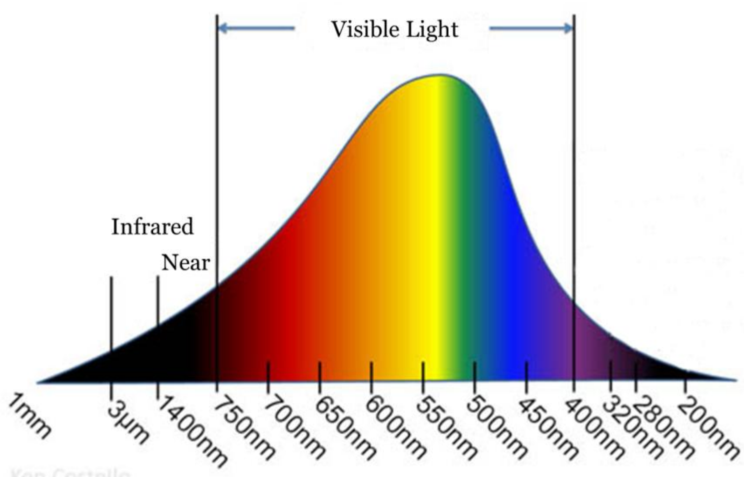
Nadir – In LiDAR, the direction pointing straight down from the bottom of the aircraft.

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 georeferenced ground positions of higher accuracy.[2] It represents the most popular accuracy standard for use in testing and reporting the accuracy for today's LiDAR projects.

Near Infrared (NIR) – Most terrestrial LiDAR sensors today use a solid-state Nd:YAG (neodymium-doped yttrium aluminum garnet, if you really have to know) 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).



---

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

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 a 0.7 meter nominal point spacing would be equivalent to a density of 2 ppsm.

Photon – A photon is 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 LiDAR point cloud is a collection of three-dimensional points, the relative intensity of the returns for these points, and metadata associated with their acquisition.

Point Data Format – The point data format is 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. This density is almost always quoted in the 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 / NPS^2

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 density of laser returns within a LiDAR project are almost always quoted in terms of the nominal number of returns within a square cell measuring one meter by one meter, with this number presented as the density in the units of ppsm.

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

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.

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*.

Relative Accuracy – The relative accuracy is a measure of the theoretical uncertainty in the location of one point within the LiDAR point cloud to the points surrounding it. The USGS LiDAR specifications call for a relative accuracy within a single swath of 7 cm, stated in terms of an RMSE, and a relative accuracy of 10 cm when comparing one swath to another adjacent swath, again in terms of an RMSE. See also *Absolute Accuracy*.

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 bathy LiDAR sensors used in bathymetric applications.

Return – A LiDAR return refers simply to the measurable reflection of the laser signal from an object on or near the ground that is provided in 3D space. This is also known as an echo.

Root Mean Square Error (RMSE) – The RMSE is 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 $RMSE_{XY}$ or $RMSE_{R}$. In terms of elevation, the value is most often referred to as RMSEz.

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. This typically provided in the units of cycles per second, or Hertz.

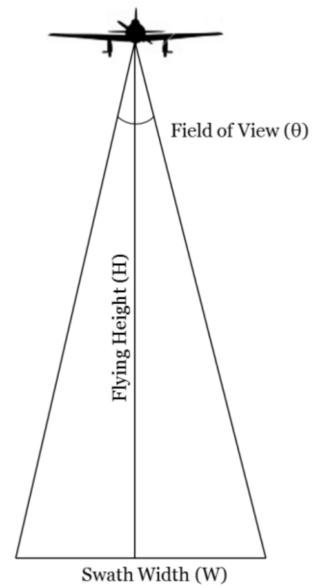
Signal to Noise Ratio (SNR) – The SNR in LiDAR represents the ratio of desired signal level to the background noise in an acquisition, with higher values generally more desirable. The SNR is a unitless number.

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 swath width in LiDAR is the width of ground coverage acquired in a single pass of the LiDAR sensor. The nominal swath width is simply a function of the field of view of the sensor and the flying height above terrain and can be determined with simple trigonometry from the graphic on the previous page. The equation is W = 2 x H x tan (theta / 2).



Wavelength – The wavelength of LiDAR is 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.