Texas Red River FEMA R6 Lidar

Report Produced for U.S. Geological Survey

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Executive Summary

The primary purpose of this project was to develop a consistent and accurate surface elevation dataset derived from high-accuracy Light Detection and Ranging (lidar) technology for the Texas Red River FEMA R6 Project Area.

The lidar data were processed and classified according to project specifications. Detailed breaklines and bare-earth Digital Elevation Models (DEMs) were produced for the project area. Data was formatted according to tiles with each tile covering an area of 1500m by 1500m. A total of 10,138 tiles were produced for the project encompassing an area of approximately 8,587 sq. miles.

THE PROJECT TEAM

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

Dewberry's Gary D. Simpson completed ground surveying for the project and delivered surveyed checkpoints. His task was to acquire surveyed checkpoints for the project to use in independent testing of the vertical accuracy of the lidar-derived surface model. He also verified the GPS base station coordinates used during lidar data acquisition to ensure that the base station coordinates were accurate. Please see the survey folder in the final deliverables to view the separate Survey Reports that were created for this portion of the project.

Quantum Spatial and Precision Aerial Reconnaissance completed lidar data acquisition and data calibration for the project area.

Kinetics completed some breakline production in a portion of TX Red River FEMA R6 Lidar Project. Dewberry was responsible for all QA/QC of the final deliverables.

SURVEY AREA

The project area addressed by this report falls within the Texas counties of McCurtain, Lamar, Red River, Bowie, Franklin, Titus, Morris, Cass, Camp, Wood, Upshur, Marion, Gregg, Smith, Harrison, Rusk, Panola, and Hopkins.

DATE OF SURVEY

The lidar aerial acquisition was conducted from January 20, 2017 to March 1, 2017.

COORDINATE REFERENCE SYSTEM

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

Horizontal Datum: The horizontal datum for the project is North American Datum of 1983 with the 2011 Adjustment (NAD 83 (2011))
Vertical Datum: The Vertical datum for the project is North American Vertical Datum of 1988 (NAVD88)
Coordinate System: UTM Zone 15
Units: Horizontal units are in meters, Vertical units are in meters.
Geiod Model: Geoid12B (Geoid 12B was used to convert ellipsoid heights to orthometric heights).

LIDAR VERTICAL ACCURACY

For the Texas Red River FEMA R6 Lidar Project, the tested $RMSE_z$ of the classified lidar data for checkpoints in non-vegetated terrain equaled **5.6 cm** compared with the 10 cm specification; and the NVA of the classified lidar data computed using $RMSE_z$ x 1.9600 was equal to **10.9 cm**, compared with the 19.6 cm specification.

For the Texas Red River FEMA R6 Lidar Project, the tested VVA of the classified lidar data computed using the 95th percentile was equal to **15.3 cm,** compared with the 29.4 cm specification.

Additional accuracy information and statistics for the classified lidar data, raw swath data, and bare earth DEM data are found in the following sections of this report.

PROJECT DELIVERABLES

The deliverables for the project are listed below.

1. Classified Point Cloud Data (Tiled)
2. Bare Earth Surface (Raster DEM – IMG Format)
3. Intensity Images (8-bit gray scale, tiled, GeoTIFF format)
4. Breakline Data (File GDB)
5. Independent Survey Checkpoint Data (Report, Photos, & Points)
6. Calibration Points
7. Metadata
8. Project Report (Acquisition, Processing, QC)
9. Project Extents, Including a shapefile derived from the lidar deliverable

PROJECT TILING FOOTPRINT

Ten thousand one hundred thirty eight (10,138) tiles were delivered for the project. Each tile's extent is 1,500 meters by 1,500 meters (see Appendix A for a complete listing of delivered tiles).

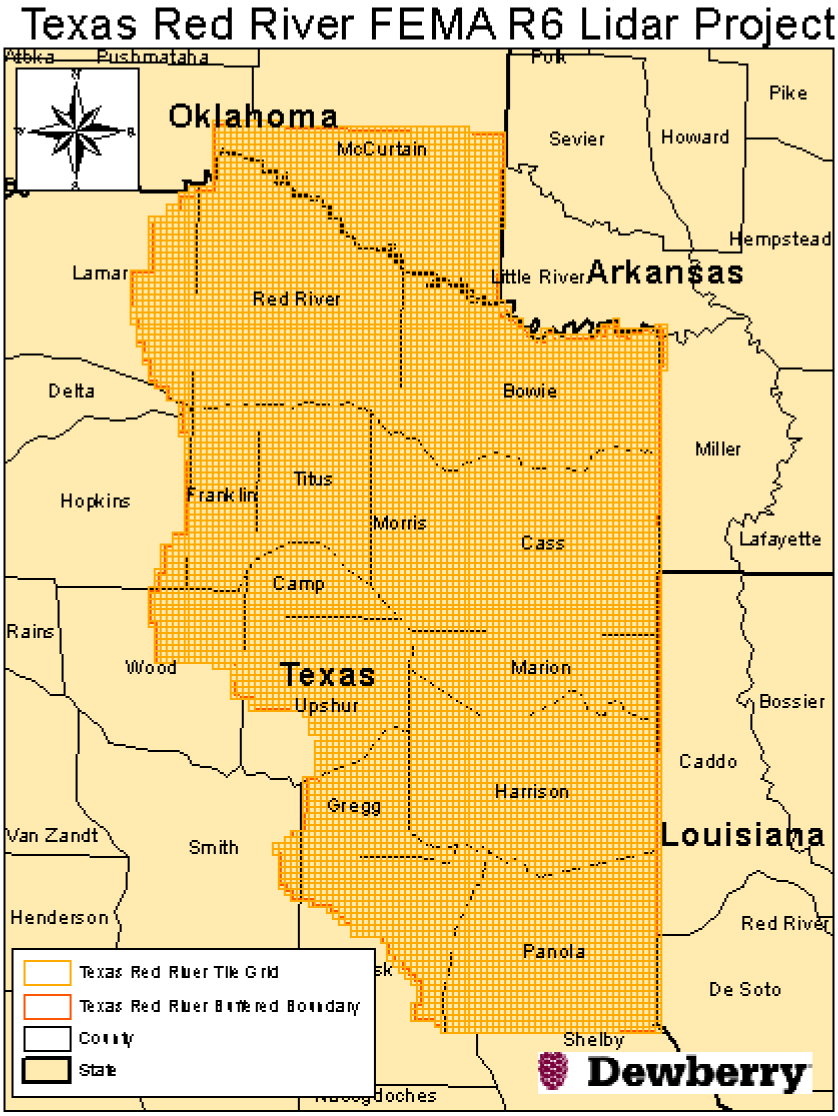


Figure 1 - Project Map

Lidar Acquisition Report

Dewberry elected to subcontract the lidar acquisition and calibration activities for approximately 5,592 square miles (additional area was collected once the 100 m buffer was applied) in the north portion of Texas Red River AOI to Quantum Spatial, Inc. Quantum Spatial was responsible for providing lidar acquisition, calibration and delivery of lidar data files to Dewberry.

Dewberry received calibrated swath data from Quantum Spatial on May 25, 2017.

LIDAR ACQUISITION DETAILS

Quantum Spatial planned 225 passes for the project area as a series of parallel flight lines with cross flightlines for the purposes of quality control. The flight plan included zigzag flight line collection as a result of the inherent IMU drift associated with all IMU systems. In order to reduce any margin for error in the flight plan, Quantum Spatial followed FEMA's Appendix A "guidelines" for flight planning and, at a minimum, includes the following criteria:

- A digital flight line layout using LEICA MISSION PRO flight design software for direct integration into the aircraft flight navigation system.
- Planned flight lines; flight line numbers; and coverage area.
- Lidar coverage extended by a predetermined margin beyond all project borders to ensure necessary over-edge coverage appropriate for specific task order deliverables.
- Local restrictions related to air space and any controlled areas have been investigated so that required permissions can be obtained in a timely manner with respect to schedule. Additionally, Quantum Spatial will file our flight plans as required by local Air Traffic Control (ATC) prior to each mission.

Quantum Spatial monitored weather and atmospheric conditions and conducted lidar missions only when no conditions exist below the sensor that will affect the collection of data. These conditions include leaf-off for hardwoods, no snow, rain, fog, smoke, mist and low clouds. Lidar systems are active sensors, not requiring light, thus missions may be conducted during night hours when weather restrictions do not prevent collection. Quantum Spatial accesses reliable weather sites and indicators (webcams) to establish the highest probability for successful collection in order to position our sensor to maximize successful data acquisition.

Within 72-hours prior to the planned day(s) of acquisition, Quantum Spatial closely monitored the weather, checking all sources for forecasts at least twice daily. As soon as weather conditions were conducive to acquisition, our aircraft mobilized to the project site to begin data collection. Once on site, the acquisition team took responsibility for weather analysis.

Quantum Spatial lidar sensors are calibrated at a designated site located at the East Texas Regional Airport in Longview, TX and are periodically checked and adjusted to minimize corrections at project sites.

LIDAR SYSTEM PARAMETERS

Quantum Spatial operated a Cessna 402 (Tail # N246MP), a Cessna Caravan (Tail # N208NR), and two Piper Navajo (Tail # N812TB, N73TM) aircraft, outfitted with LEICA ALS70-HP and LEICA ALS80 LiDAR systems during the collection of the study area. Table 1 illustrates Quantum Spatial system parameters for lidar acquisition on this project.

Item	Parameter
System	Leica ALS-70 HP, Leica ALS80
Altitude (AGL meters)	1850
Approx. Flight Speed (knots)	150
Scanner Pulse Rate (kHz)	294.6
Scan Frequency (hz)	53.4
Pulse Duration of the Scanner (nanoseconds)	2.5

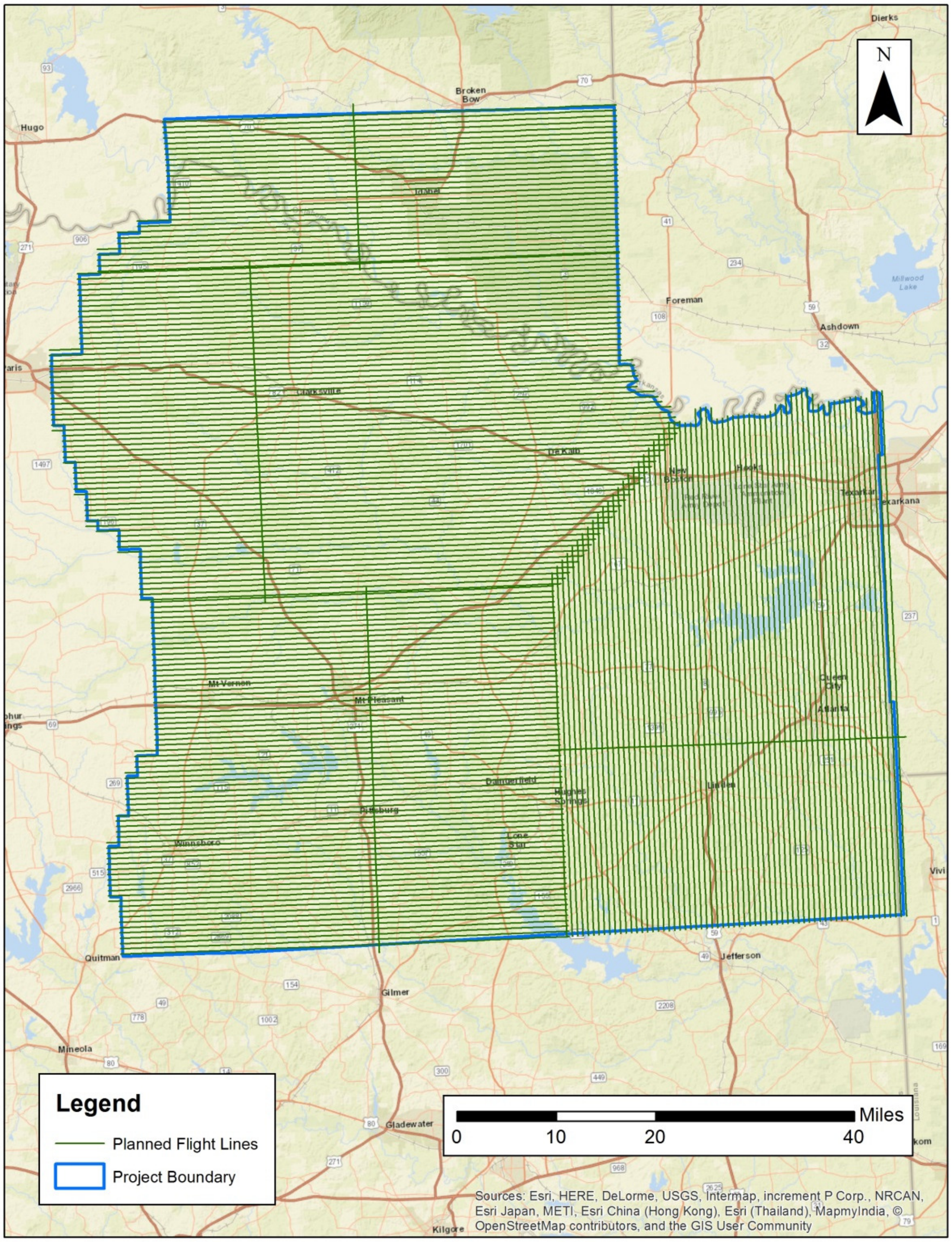
Item	Parameter
Pulse Width of the Scanner (m)	0.75
Swath width (m)	1346
Central Wavelength of the Sensor Laser (nanometers)	1064
Did the Sensor Operate with Multiple Pulses in The Air? (yes/no)	Yes
Beam Divergence (milliradians)	0.22
Nominal Swath Width on the Ground (m)	1346
Swath Overlap (%)	30
Total Sensor Scan Angle (degree)	40
Computed Down Track spacing (m) per beam	1.44
Computed Cross Track Spacing (m) per beam	1.06
Nominal Pulse Spacing (single swath), (m)	0.62
Nominal Pulse Density (single swath) (ppsm), (m)	2.6
Aggregate NPS (m) (if ANPS was designed to be met through single coverage, ANPS and NPS will be equal)	0.62
Aggregate NPD (m) (if ANPD was designed to be met through single coverage, ANPD and NPD will be equal)	2.6
Maximum Number of Returns per Pulse	4

Table 1: Quantum Spatial lidar system parameters

ACQUISITION STATUS REPORT AND FLIGHTLINES

Upon notification to proceed, the flight crew loaded the flight plans and validated the flight parameters. The Acquisition Manager contacted air traffic control and coordinated flight pattern requirements. Lidar acquisition began immediately upon notification that control base stations were in place. During flight operations, the flight crew monitored weather and atmospheric conditions. Lidar missions were flown only when no condition existed below the sensor that would affect the collection of data. The pilot constantly monitored the aircraft course, position, pitch, roll, and yaw of the aircraft. The sensor operator monitored the sensor, the status of PDOPs, and performed the first Q/C review during acquisition. The flight crew constantly reviewed weather and cloud locations. Any flight lines impacted by unfavorable conditions were marked as invalid and re-flown immediately or at an optimal time.

Figure 2 shows the combined trajectory of the flightlines.



Sources: Esri, HERE, DeLorme, USGS, Intermap, increment P Corp., NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

Figure 2: Trajectories as flown by Quantum Spatial

LIDAR CONTROL

Six existing base stations and 50 virtual base stations were used to control the lidar acquisition for Quantum Spatial's portion of the Texas Red River FEMA R6 lidar project area. The coordinates of all used base stations are provided in the table below. All control and calibration points are also provided in shapefile format as part of the final deliverables.

Name	NAD83(2011) UTM 15		Ellipsoid Ht (NAD83(2011), m)
	Easting X (m)	Northing Y (m)	
ARHP	444346.11	3728986.81	85.699
TXCR	307787.57	3720941.36	106.248
TXMA	378989.78	3600505.51	80.366
TXMV	292874.54	3671424.38	133.7
TXPA	262936.99	3728970.46	146.26
TXPI	254128.38	3512826.98	125.866
V008	369507.83	3645478.26	100.009
V009	370756.63	3698095.11	99.999
V011	347983.58	3674734.77	100.002
V012	377123.75	3699198.73	100.003
V013	365143.94	3697683.46	100.002
V014	364079.11	3645890.85	100.011
V015	376735.31	3672052.21	100.01
V028	385446.17	3702988.6	100.007
V029	384042.78	3652119.88	100.005
V067	281072.31	3644206.98	100.005
V069	338830.46	3643578.8	100.011
V070	350938.97	3704852.21	100.009
V071	334599.44	3704995.52	100.001
V072	283993.74	3650629.06	100.006
V073	341929.87	3649549.66	100.009
V074	317471.47	3637163.1	100.002
V075	394896.59	3704601.75	100.001
V078	288774.98	3665627.01	100.01
V079	341693.34	3664474.8	99.998
V082	344063.12	3672329.22	100.01
V083	289983.27	3743637.1	100.01
V084	354727.08	3742280.33	100.05
V085	287084.79	3686451.77	100.014
V087	345608.65	3685417.08	100.017
V089	304625.3	3764648.36	100.007
V090	349156.01	3764150.66	100.01
V091	377689.24	3743299.85	99.998
V092	354709.97	3732417.43	100.009
V094	367014.24	3715765.35	99.998
V095	366181.98	3715778.13	100.004
V105	337954.88	3322952.38	100.006
V106	290542.98	3656383.5	100.006
V108	338348.52	3656031.77	100.004
V112	279814.9	3713272.61	100.011
V113	360970.51	3711893.28	100.005
V118	401518.08	3708125.91	100.001
V119	400431.8	3648829.97	100.01
V121	352799.35	3722795.52	100.009
V133	354110.15	3684593.46	100.001
V134	353865.62	3637388.49	100.006
V140	393895.06	3648287.54	100.014
V141	394426.74	3699638.08	100.003
V157	389496.25	3647890.59	100.007

V158	389639.13	3693612.87	100.001
V179	390772.88	3975815.88	100.015
V180	387710.12	3696395.63	100
V181	370882.31	3691961.61	99.998
V182	370185.48	3642441.05	100.002
V184	365465.79	3639812.7	100.022
V185	365475.86	3695038.12	100.004

Table 2 – Base stations used to control lidar acquisition

AIRBORN GPS KINEMATIC

Airborne GPS data was processed using the PosPac kinematic On-The-Fly (OTF) software suite. Flights were flown with a minimum of 6 satellites in view (13° above the horizon) and with a PDOP of better than 4. Distances from base station to aircraft were kept to a maximum of 40 km.

For all flights, the GPS data can be classified as excellent, with GPS residuals of 3 cm average or better but no larger than 10 cm being recorded.

GPS processing reports for each mission are included in Appendix B.

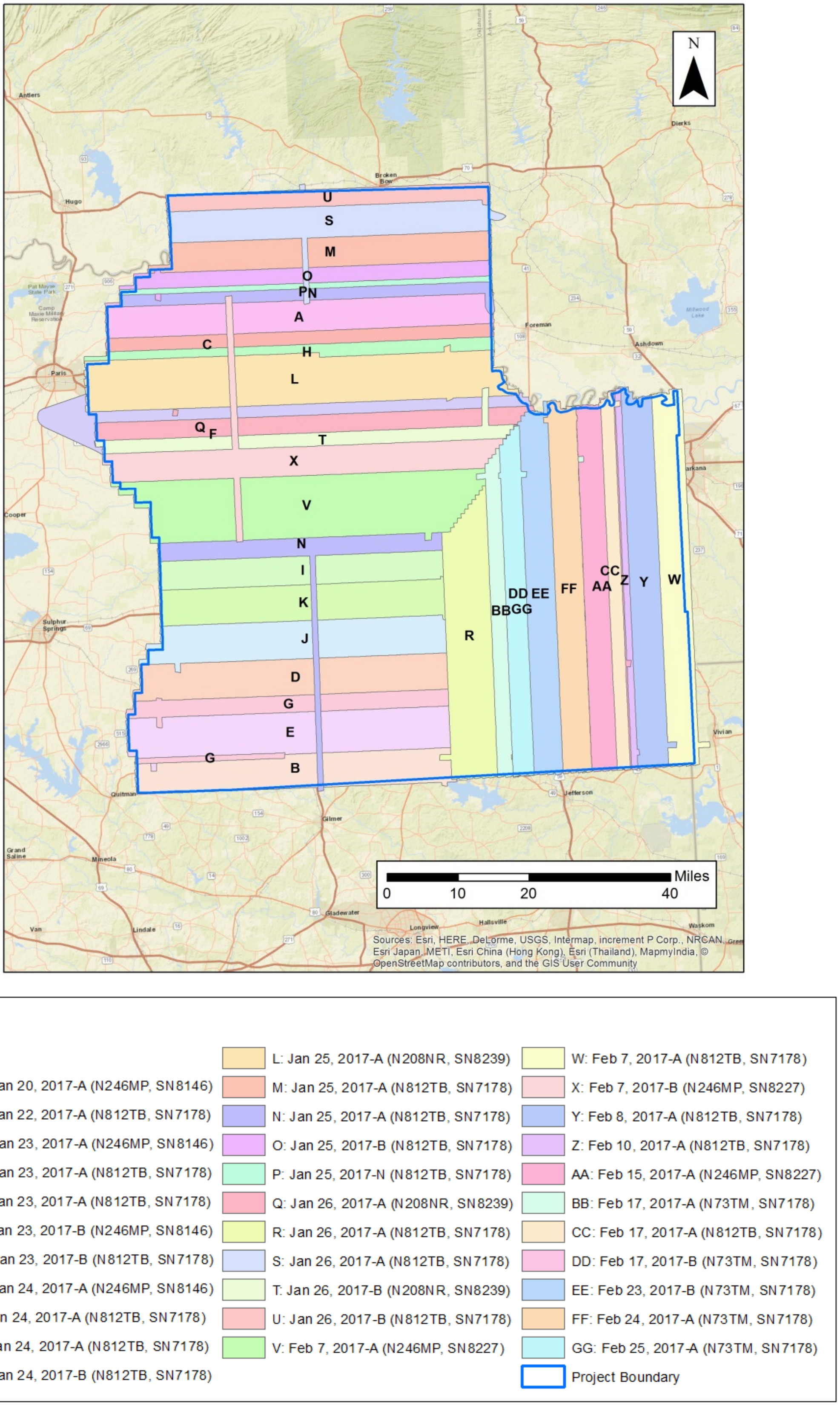
GENERATION AND CALIBRATION OF LASER POINTS (RAW DATA)

The initial step of calibration is to verify availability and status of all needed GPS and Laser data against field notes and compile any data if not complete.

Subsequently the mission points are output using Leica, initially with default values from Leica or the last mission calibrated for the system. The initial point generation for each mission calibration is verified within Microstation/Terrascan for calibration errors. If a calibration error greater than specification is observed within the mission, the roll, pitch and scanner scale corrections that need to be applied are calculated. The missions with the new calibration values are regenerated and validated internally once again to ensure quality.

Data collected by the lidar unit is reviewed for completeness, acceptable density and to make sure all data is captured without errors or corrupted values. In addition, all GPS, aircraft trajectory, mission information, and ground control files are reviewed and logged into a database.

On a project level, a supplementary coverage check is carried out to ensure no data voids unreported by Field Operations are present.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Sources: Esri, HERE, DeLorme, USGS, Intermap, increment P Corp., NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), MapmyIndia, © OpenStreetMap contributors, and the GIS User Community
Legend
Lift
A: Jan 20, 2017-A (N246MP, SN8146)
B: Jan 22, 2017-A (N812TB, SN7178)
C: Jan 23, 2017-A (N246MP, SN8146)
D: Jan 23, 2017-A (N812TB, SN7178)
E: Jan 23, 2017-A (N812TB, SN7178)
F: Jan 23, 2017-B (N246MP, SN8146)
G: Jan 23, 2017-B (N812TB, SN7178)
H: Jan 24, 2017-A (N246MP, SN8146)
I: Jan 24, 2017-A (N812TB, SN7178)
J: Jan 24, 2017-A (N812TB, SN7178)
K: Jan 24, 2017-B (N812TB, SN7178)
L: Jan 25, 2017-A (N208NR, SN8239)
M: Jan 25, 2017-A (N812TB, SN7178)
N: Jan 25, 2017-A (N812TB, SN7178)
O: Jan 25, 2017-B (N812TB, SN7178)
P: Jan 25, 2017-N (N812TB, SN7178)
Q: Jan 26, 2017-A (N208NR, SN8239)
R: Jan 26, 2017-A (N812TB, SN7178)
S: Jan 26, 2017-A (N812TB, SN7178)
T: Jan 26, 2017-B (N208NR, SN8239)
U: Jan 26, 2017-B (N812TB, SN7178)
V: Feb 7, 2017-A (N246MP, SN8227)
W: Feb 7, 2017-A (N812TB, SN7178)
X: Feb 7, 2017-B (N246MP, SN8227)
Y: Feb 8, 2017-A (N812TB, SN7178)
Z: Feb 10, 2017-A (N812TB, SN7178)
AA: Feb 15, 2017-A (N246MP, SN8227)
BB: Feb 17, 2017-A (N73TM, SN7178)
CC: Feb 17, 2017-A (N812TB, SN7178)
DD: Feb 17, 2017-B (N73TM, SN7178)
EE: Feb 23, 2017-B (N73TM, SN7178)
FF: Feb 24, 2017-A (N73TM, SN7178)
GG: Feb 25, 2017-A (N73TM, SN7178)
Project Boundary

Figure 3 – Lidar swath output showing complete coverage.

BORESIGHT AND RELATIVE ACCURACY

The initial points for each mission calibration are inspected for flight line errors, flight line overlap, slivers or gaps in the data, point data minimums, or issues with the lidar unit or GPS. Roll, pitch and scanner scale are optimized during the calibration process until the relative accuracy is met.

Relative accuracy and internal quality are checked using at least 3 regularly spaced QC blocks in which points from all lines are loaded and inspected. Vertical differences between ground surfaces of each line are displayed. Color scale is adjusted so that errors greater than the specifications are flagged. Cross sections are visually inspected across each block to validate point to point, flight line to flight line and mission to mission agreement.

For this project the specifications used are as follow:
Relative accuracy <= 6 cm maximum difference within individual swaths and <=8 cm RMSDz between adjacent and overlapping swaths.

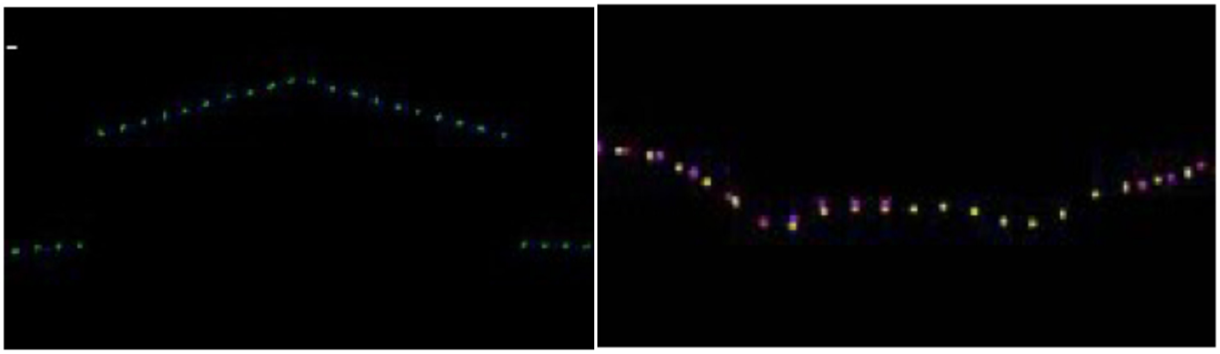

Figure 4 – Profile views showing correct roll and pitch adjustments.

PRELIMINARY VERTICAL ACCURACY ASSESSMENT

A preliminary $RMSE_z$ error check is performed by Quantum Spatial at this stage of the project life cycle in the raw lidar dataset against Ground Control Points (GCPs) surveyed by Dewberry and compared to $RMSE_z$ project specifications. The lidar data is examined in non-vegetated, flat areas away from breaks. Lidar ground points for each flight line generated by an automatic classification routine are used.

Prior to delivery to Dewberry, the elevation data was verified internally to ensure it met Non-vegetated Vertical Accuracy (NVA) requirements ($RMSE_z \leq 10$ cm and $Accuracy_z$ at the 95% confidence level ≤ 19.6 cm) when compared to GCPs. Below is a summary for the test:

The calibrated lidar dataset was tested for vertical accuracy at 95% confidence level based on (RMSEz x 1.9600) when using GCPs. Test results are listed below, for each Quantum Spatial internal production block.

Block	RMSEz	# points
Hall Miller	0.038 m	16

Idabel	0.044 m	18
Mt. Pleasant	0.071 m	30

The following are the final statistics for the GCPs used by Quantum Spatial to internally verify vertical accuracy.

Hall Miller Block

Number	NAD83(2011) UTM 15		NAVD88 (Geoid 12B)	Laser Z (m)	Delta Z
	Easting X (m)	Northing Y (m)	Known Z (m)		
GCP-237	371164.577	3673006.46	87.615	87.56	-0.055
GCP-238	360417.719	3678346.158	98.611	98.62	0.009
GCP-239	349849.05	3675146.074	101.247	101.3	0.053
GCP-250	350925.188	3683975.365	80.714	80.71	-0.004
GCP-251	351459.89	3692758.636	88.968	88.95	-0.018
GCP-252	360028.562	3691091.275	105.779	105.83	0.051
GCP-253	374709.461	3688999.538	86.938	86.92	-0.018
GCP-254	374326.183	3681802.387	78.953	78.93	-0.023
GCP-255	392980.308	3680995.17	86.14	86.1	-0.04
GCP-256	393035.538	3689258.389	72.115	72.08	-0.035
GCP-257	392858.699	3699040.886	96.183	96.26	0.077
GCP-258	375854.382	3703917.345	114.514	114.55	0.036
GCP-259	369062.454	3703854.762	109.679	109.65	-0.029
GCP-277	380204.88	3711750.818	102.002	102.01	0.008
GCP-278	395994.566	3707604.487	107.746	107.72	-0.026
GCP-237	371164.577	3673006.46	87.615	87.56	-0.055

Table 3 - GCP Points

100 % of Totals	# of Points	RMSEz (m) NVA Spec=0.1 m	NVA at 95% Spec=0.196 m	Mean (m)	Std Dev (m)	Min (m)	Max (m)
Non-Vegetated Terrain	16	0.038	0.074	-0.001	0.039	-0.055	0.077

Table 4 - GCP Vertical Accuracy Results

Idabel Block

Number	NAD83(2011) UTM 15		NAVD88 (Geoid 12B)	Laser Z (m)	Delta Z
	Easting X (m)	Northing Y (m)	Known Z (m)		
GCP-294	359952.07	3743577.934	115.363	115.45	0.087
GCP-295	350003.366	3742092.83	131.809	131.82	0.011
GCP-296	334299.975	3750019.19	138.132	138.14	0.008
GCP-297	316222.446	3745445.709	116.116	116.09	-0.026
GCP-298	308015.562	3747818.555	116.933	116.96	0.027
GCP-299	299858.671	3746121.335	136.342	136.37	0.028
GCP-300	290012.703	3745448.426	139.551	139.55	-0.001
GCP-301	282369.106	3744420.799	154.373	154.39	0.017
GCP-302	293971.747	3757460.458	120.914	120.88	-0.034
GCP-303	307116.39	3757389.755	133.333	133.31	-0.023
GCP-304	316723.759	3755581.403	135.751	135.77	0.019
GCP-305	348834.834	3753461.112	114.335	114.38	0.045
GCP-306	360121.202	3754016.78	112.868	112.87	0.002
GCP-307	361784.274	3758087.56	96.751	96.72	-0.031
GCP-308	344975.223	3763150.976	131.24	131.23	-0.01
GCP-309	334474.505	3760074.776	122.415	122.37	-0.045
GCP-310	321885.114	3761912.481	111.355	111.35	-0.005
GCP-311	307416.52	3764119.278	156.62	156.49	-0.13

Table 5 - GCP Points

100 % of Totals	# of Points	RMSEz (m) NVA Spec=0.1 m	NVA at 95% Spec=0.196 m	Mean (m)	Std Dev (m)	Min (m)	Max (m)
Non-Vegetated Terrain	18	0.044	0.086	-0.003	0.045	-0.13	0.087

Table 6 - GCP Vertical Accuracy Results

Mt. Pleasant Block

Number	NAD83(2011) UTM 15		NAVD88 (Geoid 12B)	Laser Z (m)	Delta Z
	Easting X (m)	Northing Y (m)	Known Z (m)		
GCP-195	346498.949	3630145.392	71.93	72.03	0.1
GCP-203	348710.096	3639025.106	90.175	90.25	0.075
GCP-204	338490.872	3635344.016	87.106	87.18	0.074
GCP-205	330425.868	3633755.962	127.45	127.5	0.05
GCP-206	317491.303	3637139.971	114.878	114.93	0.052
GCP-207	306346.897	3637763.72	120.973	121.02	0.047
GCP-208	293577.757	3640923.676	193.008	193.17	0.162
GCP-209	282043.906	3642027.615	142.901	142.98	0.079
GCP-210	281759.909	3652732.646	148.787	148.8	0.013
GCP-211	292998.067	3652253.839	139.872	139.95	0.078
GCP-212	306585.303	3649113.665	114.628	114.74	0.112
GCP-213	316610.212	3648837.005	114.091	114.22	0.129
GCP-214	329286.503	3647848.258	97.116	97.17	0.054
GCP-215	339836.496	3647263.778	106.769	106.85	0.081
GCP-221	347993.311	3650790.867	133.772	133.78	0.008
GCP-222	338965.316	3659072.745	131.266	131.27	0.004
GCP-223	330571.272	3656872.106	102.155	102.17	0.015
GCP-224	316990.372	3659603.011	105.771	105.8	0.029
GCP-225	303166.612	3660902.748	126.988	126.98	-0.008
GCP-226	292599.463	3663308.204	124.589	124.53	-0.059
GCP-227	292307.957	3674472.56	144.913	144.87	-0.043
GCP-228	302945.441	3672226.912	134.238	134.14	-0.098
GCP-229	317257.945	3671076.767	120.712	120.69	-0.022
GCP-230	339750.891	3670905.206	118.693	118.58	-0.113
GCP-240	337438.305	3678792.909	95.708	95.66	-0.048
GCP-241	324053.093	3678052.183	119.959	119.92	-0.039
GCP-242	316147.354	3681966.416	118.308	118.25	-0.058
GCP-243	302754.32	3683336.048	110.743	110.7	-0.043
GCP-244	291190.187	3685376.048	113.277	113.31	0.033
GCP-249	336877.624	3685907.582	90.512	90.43	-0.082

Table 7 - GCP Points

100 % of Totals	# of Points	RMSEz (m) NVA Spec=0.1 m	NVA at 95% Spec=0.196 m	Mean (m)	Std Dev (m)	Min (m)	Max (m)
Non-Vegetated Terrain	30	0.071	0.140	0.019	0.07	-0.113	0.162

Table 8 - GCP Vertical Accuracy Results

Overall the calibrated lidar data products collected by Quantum Spatial meet or exceed the requirements set out in the Statement of Work. The quality control requirements of Quantum Spatial quality management program were adhered to throughout the acquisition stage for this project to ensure product quality.

Lidar Acquisition Report

Dewberry elected to subcontract the lidar acquisition and calibration activities for approximately 2,964 square miles (additional area was collected once the 100 m buffer was applied) in the south portion of Texas Red River AOI to Precision Aerial Reconnaissance (PAR). PAR was responsible for providing lidar acquisition, calibration and delivery of lidar data files to Dewberry.

Dewberry received calibrated swath data from PAR on May 22, 2017.

LIDAR ACQUISITION DETAILS

PAR planned 219 passes for the project area as a series of parallel flight lines with cross flightlines for the purposes of quality control. The flight plan included zigzag flight line collection as a result of the inherent IMU drift associated with all IMU systems. In order to reduce any margin for error in the flight plan, PAR followed FEMA's Appendix A "guidelines" for flight planning and, at a minimum, includes the following criteria:

- A digital flight line layout using LEICA MISSION PRO flight design software for direct integration into the aircraft flight navigation system.
- Planned flight lines; flight line numbers; and coverage area.
- Lidar coverage extended by a predetermined margin beyond all project borders to ensure necessary over-edge coverage appropriate for specific task order deliverables.
- Local restrictions related to air space and any controlled areas have been investigated so that required permissions can be obtained in a timely manner with respect to schedule. Additionally, Quantum Spatial will file our flight plans as required by local Air Traffic Control (ATC) prior to each mission.

PAR monitored weather and atmospheric conditions and conducted lidar missions only when no conditions exist below the sensor that will affect the collection of data. These conditions include leaf-off for hardwoods, no snow, rain, fog, smoke, mist and low clouds. Lidar systems are active sensors, not requiring light, thus missions may be conducted during night hours when weather restrictions do not prevent collection. PAR accesses reliable weather sites and indicators (webcams) to establish the highest probability for successful collection in order to position our sensor to maximize successful data acquisition.

Within 72-hours prior to the planned day(s) of acquisition, PAR closely monitored the weather, checking all sources for forecasts at least twice daily. As soon as weather conditions were conducive to acquisition, our aircraft mobilized to the project site to begin data collection. Once on site, the acquisition team took responsibility for weather analysis.

LIDAR SYSTEM PARAMETERS

PAR operated a Cessna 206 (Tail # N799AC) outfitted with a LEICA ALS70-HP LiDAR system during the collection of the study area. Table 9 illustrates PAR system parameters for lidar acquisition on this project.

Item	Parameter
System	Leica ALS-70 HP
Altitude (AGL meters)	1900
Approx. Flight Speed (knots)	115
Scanner Pulse Rate (kHz)	270
Scan Frequency (hz)	46
Pulse Duration of the Scanner (nanoseconds)	2.5
Pulse Width of the Scanner (m)	0.75
Swath width (m)	1383
Central Wavelength of the Sensor Laser (nanometers)	1064
Did the Sensor Operate with Multiple Pulses in The Air? (yes/no)	Yes
Beam Divergence (milliradians)	0.22
Nominal Swath Width on the Ground (m)	1383
Swath Overlap (%)	30
Total Sensor Scan Angle (degree)	40
Computed Down Track spacing (m) per beam	0.58
Computed Cross Track Spacing (m) per beam	0.64
Nominal Pulse Spacing (single swath), (m)	0.64
Nominal Pulse Density (single swath) (ppsm), (m)	2.44
Aggregate NPS (m) (if ANPS was designed to be met through single coverage, ANPS and NPS will be equal)	0.64
Aggregate NPD (m) (if ANPD was designed to be met through single coverage, ANPD and NPD will be equal)	2.44
Maximum Number of Returns per Pulse	4

Table 9: PAR lidar system parameters

ACQUISITION STATUS REPORT AND FLIGHTLINES

Upon notification to proceed, the flight crew loaded the flight plans and validated the flight parameters. The Acquisition Manager contacted air traffic control and coordinated flight pattern requirements. Lidar acquisition began immediately upon notification that control base stations were in place. During flight operations, the flight crew monitored weather and atmospheric conditions. Lidar missions were flown only when no condition existed below the sensor that would affect the collection of data. The pilot constantly monitored the aircraft course, position, pitch, roll, and yaw of the aircraft. The sensor operator monitored the sensor, the status of PDOPs, and performed the first Q/C review during acquisition. The flight crew constantly reviewed weather and cloud locations. Any flight lines impacted by unfavorable conditions were marked as invalid and re-flown immediately or at an optimal time.

Figure 5 shows the combined trajectory of the flightlines.

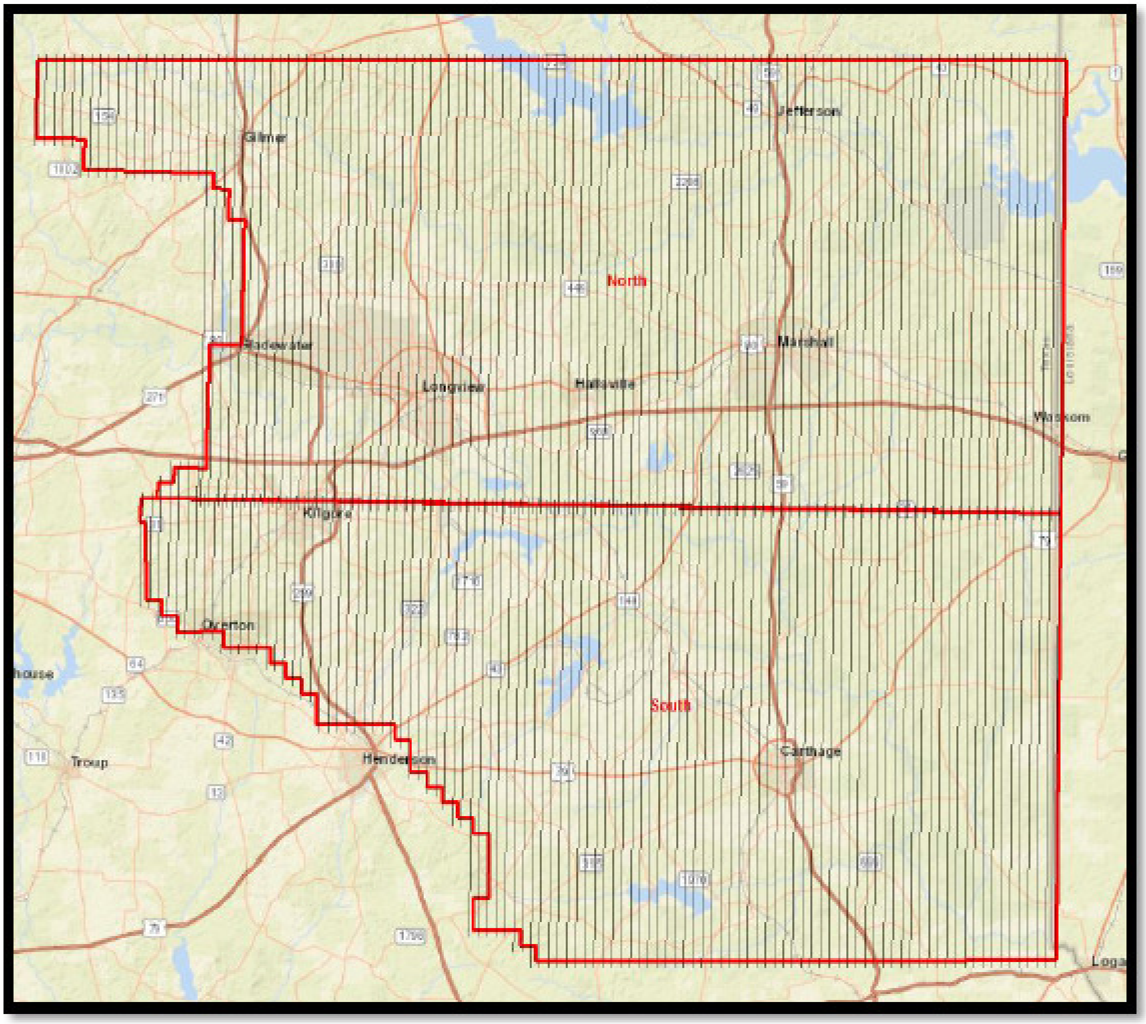

Figure 5: Trajectories as flown by PAR

LIDAR CONTROL

Three existing base stations and one virtual base stations were used to control the lidar acquisition for PAR's portion of the Texas Red River FEMA R6 lidar project area. The coordinates of all used base stations are provided in the table below. All control and calibration points are also provided in shapefile format as part of the final deliverables.

Name	NAD83(2011) UTM 15		Ellipsoid Ht (NAD83(2011), m)	Orthometric Ht (NAVD88 Geoid12B, m)
	Easting X (m)	Northing Y (m)		
AB2800	376,831.271	3,598,888.116	80.096	106.36
CR1361	317340.638	3619683.382	96.745	123.30
OPUS1	338151.271	3584098.051	85.587	111.979
CR1356	377659.604	3560395.003	48.081	74.32

Table 10 – Base stations used to control lidar acquisition

AIRBORN GPS KINEMATIC

Airborne GPS data was processed using the PosPac kinematic On-The-Fly (OTF) software suite. Flights were flown with a minimum of 6 satellites in view (13° above the horizon) and with a PDOP of better than 4. Distances from base station to aircraft were kept to a maximum of 40 km.

For all flights, the GPS data can be classified as excellent, with GPS residuals of 3 cm average or better but no larger than 10 cm being recorded.

GPS processing reports for each mission are included in Appendix C.

GENERATION AND CALIBRATION OF LASER POINTS (RAW DATA)

The initial step of calibration is to verify availability and status of all needed GPS and Laser data against field notes and compile any data if not complete.

Subsequently the mission points are output using Leica, initially with default values from Leica or the last mission calibrated for the system. The initial point generation for each mission calibration is verified within Microstation/Terrascan for calibration errors. If a calibration error greater than specification is observed within the mission, the roll, pitch and scanner scale corrections that need to be applied are calculated. The missions with the new calibration values are regenerated and validated internally once again to ensure quality.

Data collected by the lidar unit is reviewed for completeness, acceptable density and to make sure all data is captured without errors or corrupted values. In addition, all GPS, aircraft trajectory, mission information, and ground control files are reviewed and logged into a database.

On a project level, a supplementary coverage check is carried out to ensure no data voids unreported by Field Operations are present.

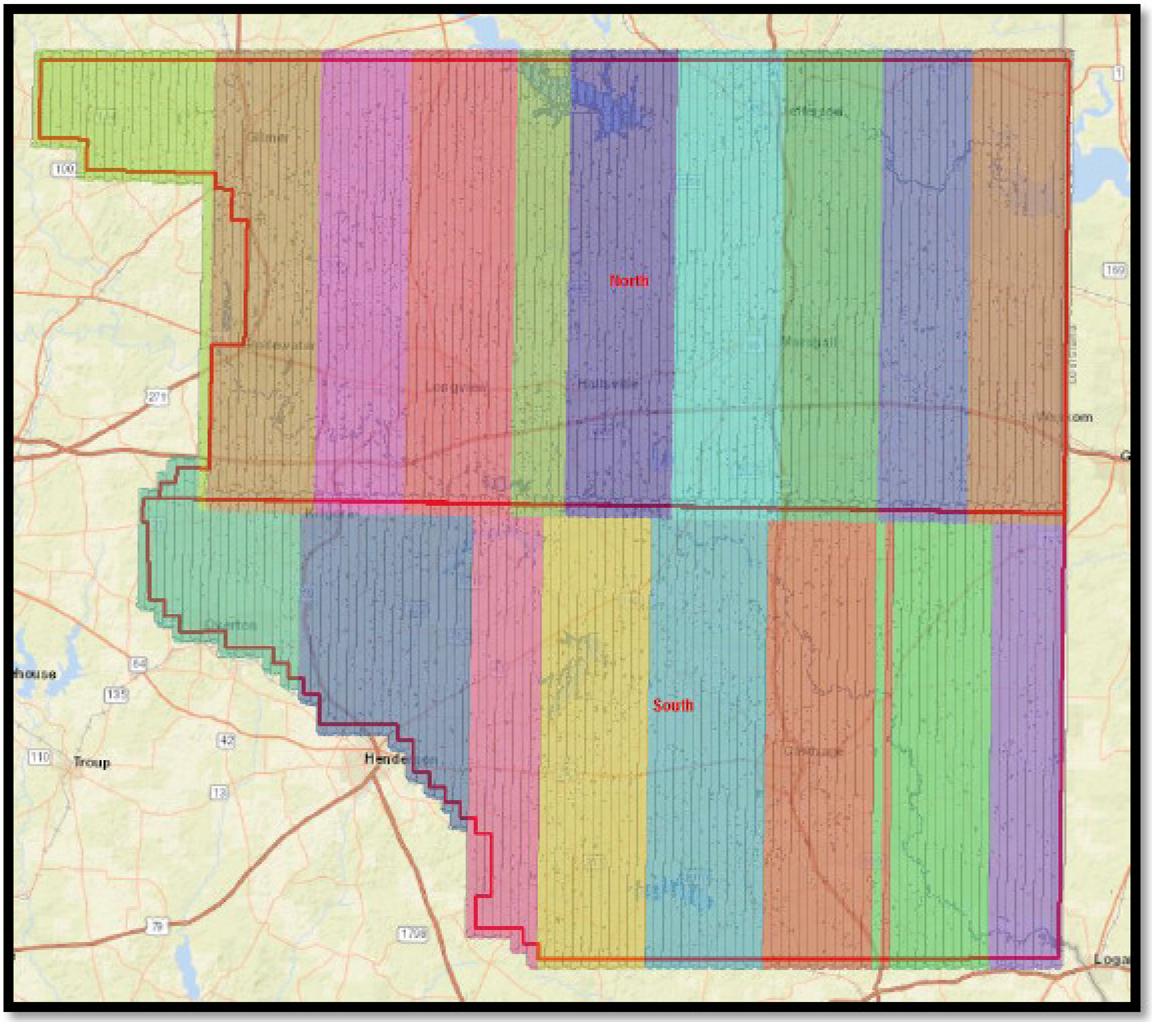

Figure 6 – Lidar swath output showing complete coverage.

BORESIGHT AND RELATIVE ACCURACY

The initial points for each mission calibration are inspected for flight line errors, flight line overlap, slivers or gaps in the data, point data minimums, or issues with the lidar unit or GPS. Roll, pitch and scanner scale are optimized during the calibration process until the relative accuracy is met.

Relative accuracy and internal quality are checked using at least 3 regularly spaced QC blocks in which points from all lines are loaded and inspected. Vertical differences between ground surfaces of each line are displayed. Color scale is adjusted so that errors greater than the specifications are flagged. Cross sections are visually inspected across each block to validate point to point, flight line to flight line and mission to mission agreement.

For this project the specifications used are as follow:
Relative accuracy <= 6 cm maximum difference within individual swaths and <=8 cm RMSDz between adjacent and overlapping swaths.

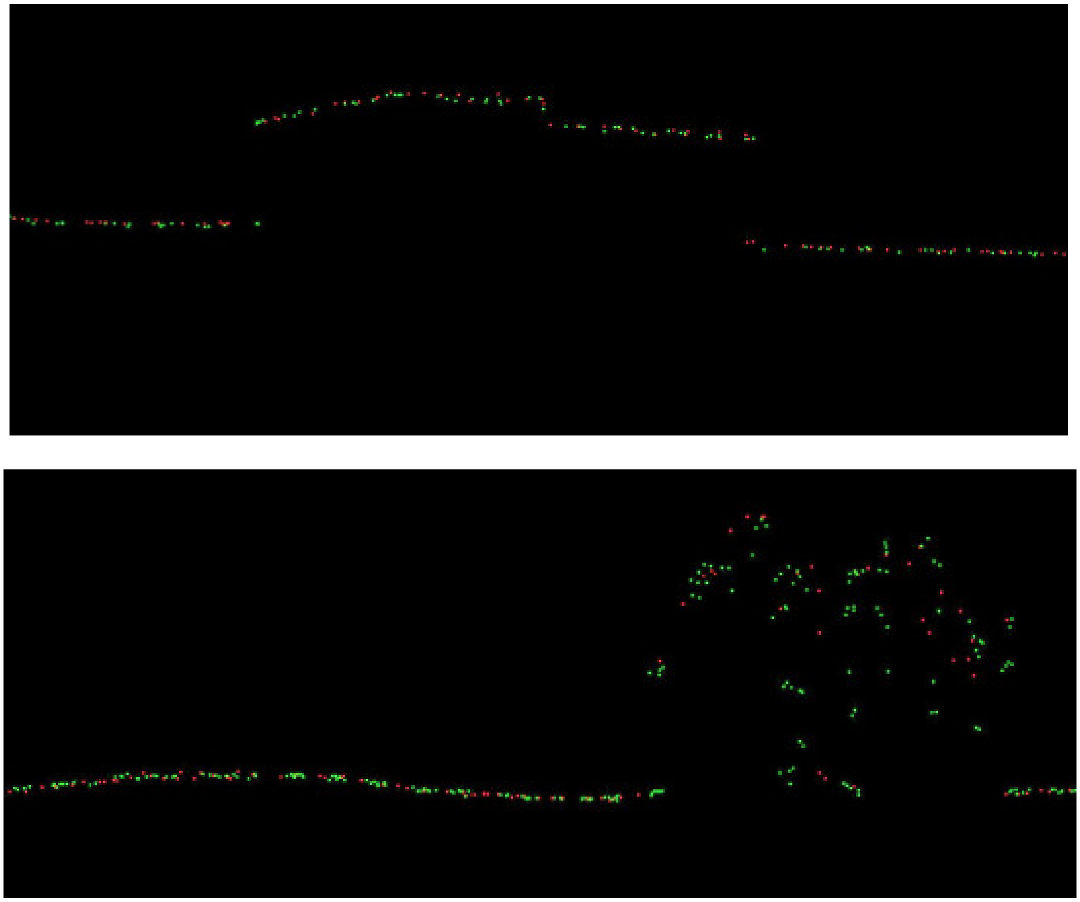

Figure 7 – Profile views showing correct roll and pitch adjustments.

PRELIMINARY VERTICAL ACCURACY ASSESSMENT

A preliminary $RMSE_z$ error check is performed by PAR at this stage of the project life cycle in the raw lidar dataset against Ground Control Points (GCPs) surveyed by Dewberry and compared to $RMSE_z$ project specifications. The lidar data is examined in non-vegetated, flat areas away from breaks. Lidar ground points for each flight line generated by an automatic classification routine are used.

Prior to delivery to Dewberry, the elevation data was verified internally to ensure it met Non-vegetated Vertical Accuracy (NVA) requirements ($RMSE_z \leq 10$ cm and $Accuracy_z$ at the 95% confidence level ≤ 19.6 cm) when compared to GCPs.

The calibrated lidar dataset was tested to 0.104 m vertical accuracy at the 95% confidence level based on $RMSE_z$ (0.053 m x 1.9600) when compared to 72 GCPs.

The following are the final statistics for the GCPs used by PAR to internally verify vertical accuracy.

Number	NAD83(2011) UTM 15		NAVD88 (Geoid 12B)	Laser Z (m)	Delta Z
	Easting X (m)	Northing Y (m)	Known Z (m)		
GCP-123	3544108.014	347977.465	103.115	103.114	-0.006
GCP-125	3543601.977	367875.908	97.530	97.560	+0.030
GCP-126	3542058.025	377153.725	95.849	95.819	-0.031
GCP-127	3543581.365	387292.431	77.859	77.870	+0.010
GCP-128	3543302.500	397186.244	63.394	63.474	+0.084
GCP-129	3553860.153	395884.859	85.748	85.769	+0.019
GCP-130	3554261.801	388410.353	60.655	60.680	+0.020
GCP-131	3553989.044	378717.387	83.010	82.980	-0.030
GCP-132	3553860.164	368626.817	85.639	85.552	-0.088
GCP-135	3565126.892	329546.687	132.306	132.319	+0.009
GCP-136	3565760.792	339017.578	131.090	131.123	+0.033
GCP-139	3564206.210	368434.029	96.401	96.525	+0.125
GCP-140	3565164.785	376906.813	72.576	72.605	+0.025
GCP-141	3564769.880	389640.150	92.020	92.034	+0.014
GCP-142	3563452.115	399034.298	89.176	89.161	-0.019
GCP-143	3574614.804	396740.905	89.383	89.387	+0.007
GCP-144	3574915.151	387748.130	101.665	101.651	-0.019
GCP-145	3574789.905	378250.850	72.188	72.200	+0.010
GCP-146	3575584.886	368056.716	92.245	92.231	-0.019
GCP-148	3575448.855	348321.659	129.792	129.815	+0.025
GCP-149	3574763.879	339942.637	133.304	133.349	+0.049
GCP-150	3575821.786	329346.662	102.488	102.563	+0.073
GCP-151	3575928.618	320588.391	155.612	155.609	-0.001
GCP-152	3575747.485	310430.528	141.898	142.003	+0.103
GCP-153	3585827.801	310276.904	138.020	138.041	+0.021
GCP-154	3586084.827	319971.043	105.411	105.461	+0.051
GCP-155	3585746.058	330004.322	110.505	110.548	+0.038
GCP-156	3585649.749	339415.231	103.457	103.521	+0.061
GCP-157	3589202.061	350079.765	79.016	79.036	+0.016
GCP-159	3584562.823	369219.130	84.589	84.631	+0.041
GCP-160	3585328.671	379145.958	103.598	103.649	+0.049
GCP-161	3584843.092	387595.876	115.170	115.237	+0.067
GCP-162	3585502.094	397760.427	99.886	99.825	-0.065
GCP-163	3595137.459	397767.381	83.563	83.565	+0.005
GCP-164	3595435.121	388548.087	93.488	93.493	+0.003
GCP-165	3595789.871	378275.842	86.952	86.965	+0.015
GCP-166	3595427.545	367616.792	122.905	122.937	+0.027
GCP-167	3595777.466	359232.306	106.009	105.969	-0.041
GCP-168	3595926.331	349399.036	102.075	102.126	+0.046
GCP-169	3596042.736	339591.735	102.414	102.425	+0.015
GCP-170	3596026.981	329856.616	102.235	102.252	+0.012

GCP-171	3595827.403	319673.935	86.283	86.327	+0.047
GCP-172	3606477.319	320491.864	119.020	119.120	+0.100
GCP-173	3606542.608	329787.822	132.272	132.373	+0.103
GCP-174	3606308.082	339830.741	130.927	130.929	-0.001
GCP-175	3605765.044	349771.713	104.859	104.921	+0.061
GCP-176	3606200.657	358400.035	77.635	77.668	+0.028
GCP-177	3605733.613	369079.569	100.861	100.816	-0.044
GCP-178	3606185.271	379864.569	103.681	103.646	-0.034
GCP-179	3605879.553	388442.770	85.914	85.949	+0.039
GCP-180	3606336.272	396329.885	92.491	92.557	+0.067
GCP-181	3615944.644	396850.541	57.595	57.620	+0.020
GCP-182	3616462.233	388631.505	85.654	85.738	+0.088
GCP-183	3615739.907	378500.360	92.536	92.538	-0.002
GCP-184	3616109.409	369745.995	73.101	73.180	+0.080
GCP-185	3616666.387	359054.379	77.818	77.877	+0.057
GCP-186	3616647.141	349907.990	80.000	79.950	-0.050
GCP-187	3617114.387	341087.540	88.783	88.818	+0.038
GCP-188	3617334.550	330909.223	100.832	100.811	-0.019
GCP-189	3617038.595	321549.540	118.539	118.618	+0.078
GCP-190	3627748.526	300982.714	142.177	142.250	+0.070
GCP-191	3627135.174	310362.117	120.854	120.965	+0.115
GCP-192	3627510.577	320848.957	86.383	86.468	+0.088
GCP-193	3628319.533	329317.988	110.045	110.048	-0.002
GCP-194	3627005.223	340492.620	113.967	113.932	-0.038
GCP-195	3630145.392	346498.949	71.930	72.028	+0.098
GCP-196	3627334.919	359744.102	98.292	98.302	+0.012
GCP-197	3627044.596	369244.639	93.130	93.084	-0.046
GCP-198	3629162.299	381120.048	91.243	91.390	+0.150
GCP-199	3626661.240	389157.683	62.135	62.191	+0.051
GCP-200	3626511.544	399517.208	72.969	73.002	+0.032

Table 11 - GCP Points

100 % of Totals	# of Points	RMSEz (m) NVA Spec=0.1 m	NVA at 95% Spec=0.196 m	Mean (m)	Std Dev (m)	Min (m)	Max (m)
Non-Vegetated Terrain	72	0.053	0.104	0.028	0.048	-0.088	0.150

Table 12 - GCP Vertical Accuracy Results

Overall the calibrated lidar data products collected by PAR meet or exceed the requirements set out in the Statement of Work. The quality control requirements of PAR's quality management program were adhered to throughout the acquisition stage for this project to ensure product quality.

Lidar Processing & Qualitative Assessment

INITIAL PROCESSING

Once Dewberry receives the calibrated swath data from the acquisition provider, Dewberry performs several validations on the dataset prior to starting full-scale production on the project. These validations include vertical accuracy of the swath data, inter-swath (between swath) relative accuracy validation, intra-swath (within a single swath) relative accuracy validation, verification of horizontal alignment between swaths, and confirmation of point density and spatial distribution. This initial assessment allows Dewberry to determine if the data are suitable for full-scale production. Addressing issues at this stage allows the data to be corrected while imposing the least disruption possible on the overall production workflow and overall schedule.

Final Swath Vertical Accuracy Assessment

Once Dewberry received the calibrated swath data from Quantum Spatial and Precision Aerial Reconnaissance, Dewberry tested the vertical accuracy of the non-vegetated terrain swath data prior to additional processing. Dewberry tested the vertical accuracy of the swath data using the one hundred forty eight non-vegetated (open terrain and urban) independent survey check points. The vertical accuracy is tested by comparing survey checkpoints in non-vegetated terrain to a triangulated irregular network (TIN) that is created from the raw swath points. Only checkpoints in non-vegetated terrain can be tested against raw swath data because the data has not undergone classification techniques to remove vegetation, buildings, and other artifacts from the ground surface. Checkpoints are always compared to interpolated surfaces from the lidar point cloud because it is unlikely that a survey checkpoint will be located at the location of a discrete lidar point. Dewberry typically uses LP360 software to test the swath lidar vertical accuracy, Terrascan software to test the classified lidar vertical accuracy, and Esri ArcMap to test the DEM vertical accuracy so that three different software programs are used to validate the vertical accuracy for each project. Project specifications require a NVA of 19.6 cm based on the $RMSE_z$ (10 cm) x 1.96. The dataset for the Texas Red River FEMA R6 Lidar Project satisfies this criteria. This raw lidar swath data set was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 10 cm $RMSE_z$ Vertical Accuracy Class. Actual NVA accuracy was found to be $RMSE_z$ = 6.3 cm, equating to +/- 12.4 cm at 95% confidence level. The table below shows all calculated statistics for the raw swath data.

100 % of Totals	# of Points	$RMSE_z$ NVA Spec=0.10 m	NVA –Non-vegetated Vertical Accuracy ($RMSE_z$ x 1.9600) Spec=0.196 m	Mean (m)	Median (m)	Skew	Std Dev (m)	Min (m)	Max (m)	Kurtosis
Non-Vegetated Terrain	148	0.063	0.124	0.007	0.012	-0.939	0.063	-0.301	0.134	3.247

Table 13: NVA at 95% Confidence Level for Raw Swaths

Inter-Swath (Between Swath) Relative Accuracy

Dewberry verified inter-swath or between swath relative accuracy of the dataset by creating Delta-Z (DZ) orthos. According to the SOW, USGS Lidar Base Specifications v1.2, and ASPRS

Positional Accuracy Standards for Digital Geospatial Data, 10 cm Vertical Accuracy Class or QL2 data must meet inter-swath relative accuracy of 8 cm RMSDz or less with maximum differences less than 16 cm. These measurements are to be taken in non-vegetated and flat open terrain using single or only returns from all classes. Measurements are calculated in the DZ orthos on 1-meter pixels or cell sizes. Areas in the dataset where overlapping flight lines are within 8 cm of each other within each pixel are colored green, areas in the dataset where overlapping flight lines have elevation differences in each pixel between 8 cm to 16 cm are colored yellow, and areas in the dataset where overlapping flight lines have elevation differences in each pixel greater than 16 cm are colored red. Pixels that do not contain points from overlapping flight lines are colored according to their intensity values. Areas of vegetation and steep slopes (slopes with 16 cm or more of valid elevation change across 1 linear meter) are expected to appear yellow or red in the DZ orthos. If the project area is heavily vegetated, Dewberry may also create DZ Orthos from the initial ground classification only, while keeping all other parameters consistent. This allows Dewberry to review the ground classification relative accuracy beneath vegetation and to ensure flight line ridges or other issues do not exist in the final classified data.

Flat, open areas are expected to be green in the DZ orthos. Large or continuous sections of yellow or red pixels can indicate the data was not calibrated correctly or that there were issues during acquisition that could affect the usability of the data, especially when these yellow/red sections follow the flight lines and not the terrain or areas of vegetation. The DZ orthos for Texas Red River FEMA R6 Lidar Project are shown in the figure below; this project meets inter-swath relative accuracy specifications.

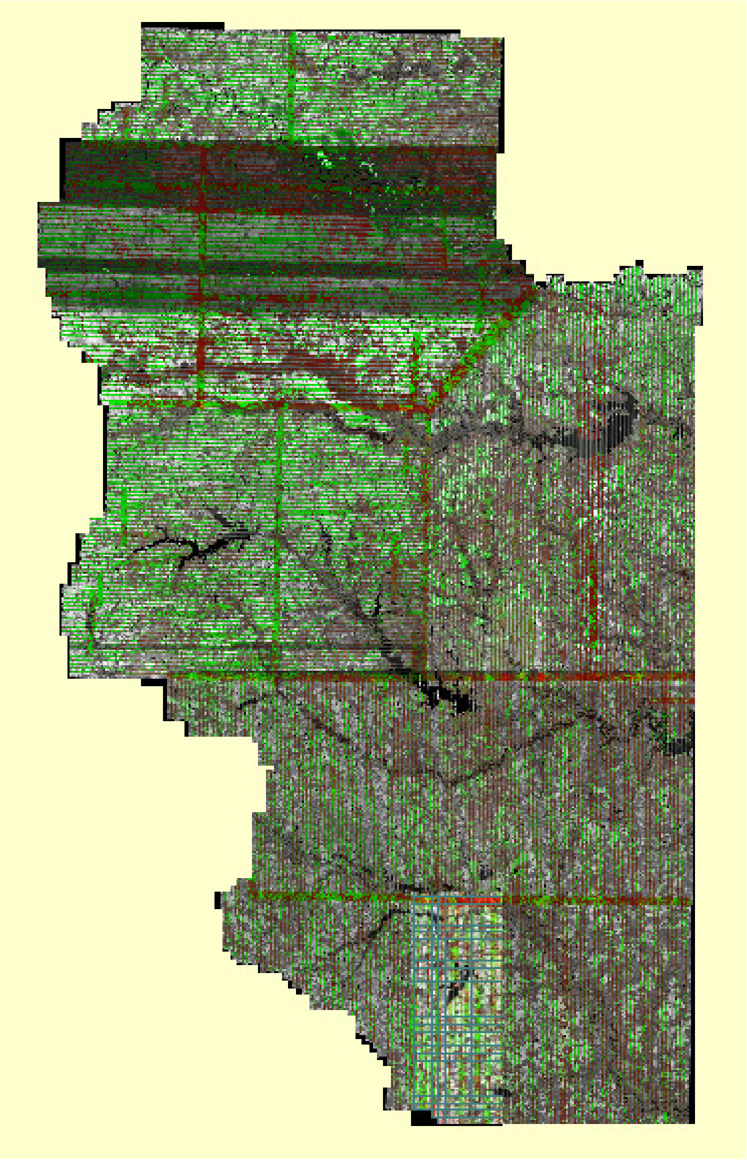

Figure 8– Single return DZ Orthos for the Texas Red River FEMA R6 Lidar Project. Inter-swath relative accuracy passes specifications.

Intra-Swath (Within a Single Swath) Relative Accuracy

Dewberry verifies the intra-swath or within swath relative accuracy by using Quick Terrain Modeler (QTM) scripting and visual reviews. QTM scripting is used to calculate the maximum difference of all points within each 1-meter pixel/cell size of each swath. Dewberry analysts then identify planar surfaces acceptable for repeatability testing and analysts review the QTM results in those areas. According to the SOW, USGS Lidar Base Specifications v1.2, and ASPRS Positional Accuracy Standards for Digital Geospatial Data, 10 cm Vertical Accuracy Class or QL2 data must meet intra-swath relative accuracy of 6 cm maximum difference or less. The image below shows an example of the intra-swath relative accuracy of Texas Red River FEMA R6 Lidar Project; this project meets intra-swath relative accuracy specifications.

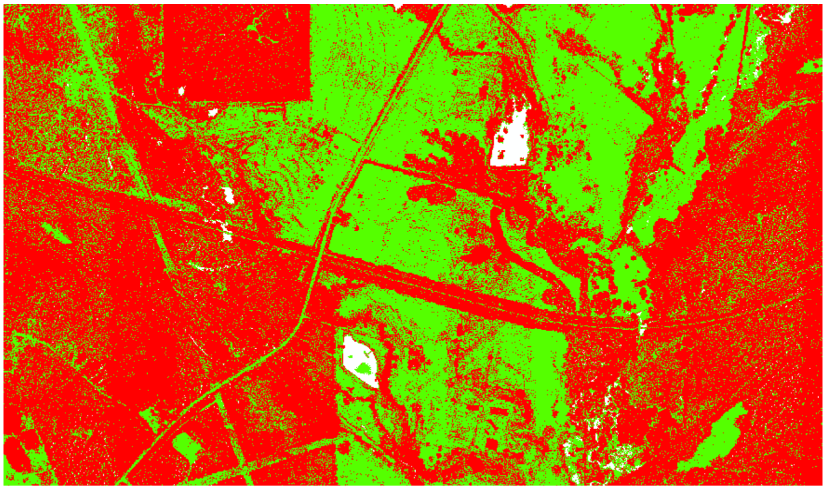

Figure 9–Intra-swath relative accuracy. The image shows a portion of the project area; areas where the maximum difference is ≤6 cm per pixel within each swath are colored green and areas exceeding 6 cm are colored red. Areas of vegetation and slope will show as red. Flat, open areas suitable for repeatability testing are green as they are within specification. Intra-swath relative accuracy passes specifications.

Horizontal Alignment

To ensure horizontal alignment between adjacent or overlapping flight lines, Dewberry uses QTM scripting and visual reviews. QTM scripting is used to create files similar to DZ orthos for each swath but this process highlights planar surfaces, such as roof tops. In particular, horizontal shifts or misalignments between swaths on roof tops and other elevated planar surfaces are highlighted. Visual reviews of these features, including additional profile verifications, are used to confirm the results of this process. The image below shows an example of the horizontal alignment between swaths for Texas Red River FEMA R6 Lidar Project; no horizontal alignment issues were identified.

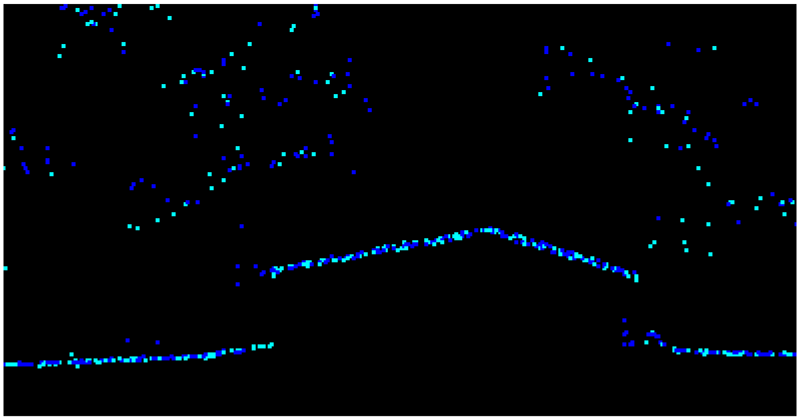

Figure 10– Horizontal Alignment. Two separate flight lines differentiated by color (Green/Blue) are shown in this profile. There is no visible offset between these two flight lines. No horizontal alignment issues were identified.

Point Density and Spatial Distribution

The required Aggregate Nominal Point Spacing (ANPS) for this project is no greater than 0.71 meters, which equates to an Aggregate Nominal Point Density (ANPD) of 2 points per square meter or greater. Density calculations were performed using first return data only located in the geometrically usable center portion (typically ~90%) of each swath. By utilizing statistics, the project area was determined to have an ANPS of 0.63 meters or an ANPD of 2.52 points per square meter which satisfies the project requirements. A visual review of a 1-square meter density grid (figure below) shows that there are some 1-meter cells that do not contain 2 points per square meter (red areas) due to the irregular spacing of lidar point cloud data. Most 1-sqaure meter cells contain at least 2 points per square meter (green areas) and when density is viewed/analyzed by representative 1-square kilometer areas (to account for the irregular spacing of lidar point clouds), density passes with no issues.

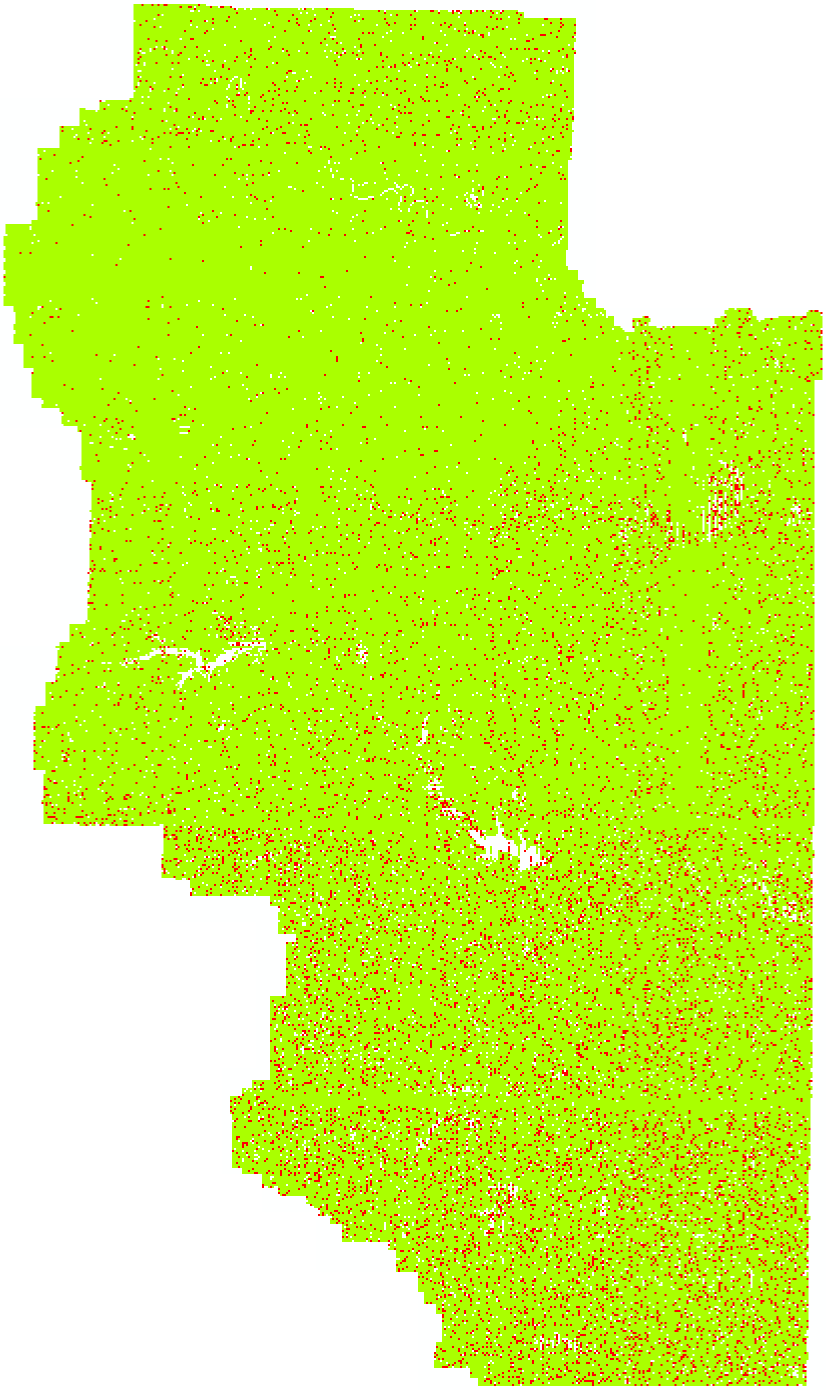

Figure 11– 1-square meter density grid. There are some 1-meter cells that do not contain 2 points per square meter (red areas) due to the irregular spacing of lidar point cloud data. Most 1-sqaure meter cells contain at least 2 points per square meter (green areas) showing there are no systematic density issues. When density is viewed/analyzed by representative 1-square kilometer areas, density passes with no issues.

The spatial distribution of points must be uniform and free of clustering. This specification is tested by creating a grid with cell sizes equal to the design NPS*2. ArcGIS tools are then used to calculate the number of first return points of each swath within each grid cell. At least 90% of the cells must contain 1 lidar point, excluding acceptable void areas such as water or low NIR reflectivity features, i.e. some asphalt and roof composition materials. This project passes spatial distribution requirements, as shown in the image below.

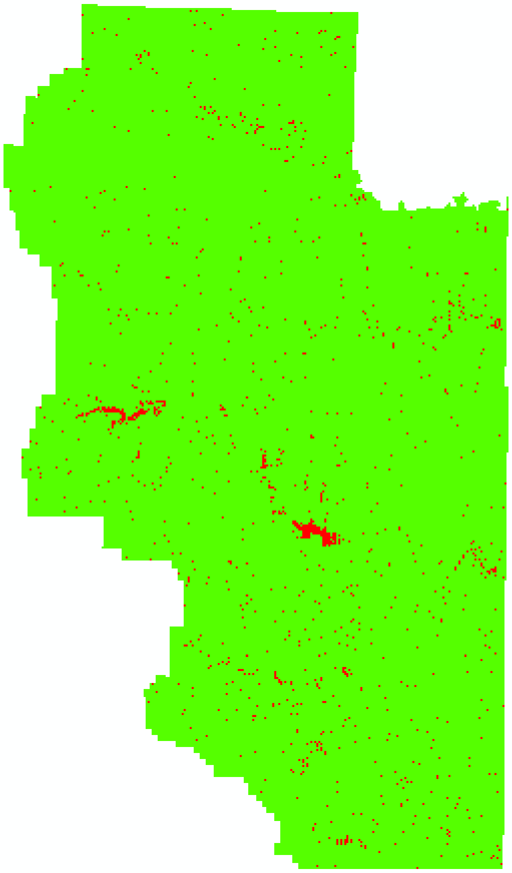

Figure 12– Spatial Distribution. All cells (2*NPS cellsize) containing at least one lidar point are colored green. Cells that do not contain a lidar point, including water bodies which are acceptable NoData area, are colored red. Without removing acceptable NoData areas due to water, 98.4% of cells contain at least one lidar point.

DATA CLASSIFICATION AND EDITING

Once the calibration, absolute swath vertical accuracy, and relative accuracy of the data was confirmed, Dewberry utilized a variety of software suites for data processing. The data was processed using GeoCue and TerraScan software. The initial step is the setup of the GeoCue project, which is done by importing a project defined tile boundary index encompassing the entire project area. The acquired 3D laser point clouds, in LAS binary format, were imported into the GeoCue project and tiled according to the project tile grid. Once tiled, the laser points were classified using a proprietary routine in TerraScan. This routine classifies any obvious low outliers in the dataset to class 7 and high outliers in the dataset to class 18. Points along flight line edges that are geometrically unusable are identified as withheld and classified to a separate class so that they will not be used in the initial ground algorithm. After points that could negatively affect the ground are removed from class 1, the ground layer is extracted from this remaining point cloud. The ground extraction process encompassed in this routine takes place by building an iterative surface model.

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

Each tile was then imported into Terrascan and a surface model was created to examine the ground classification. Dewberry analysts visually reviewed the ground surface model and corrected errors in the ground classification such as vegetation, buildings, and bridges that were present following the initial processing conducted by Dewberry. Dewberry analysts employ 3D visualization techniques to view the point cloud at multiple angles and in profile to ensure that non-ground points are removed from the ground classification. Bridge decks are classified to class 17 using bridge breaklines compiled by Dewberry. After the ground classification corrections were completed, the dataset was processed through a water classification routine that utilizes breaklines compiled by Dewberry to automatically classify hydro features. The water classification routine selects ground points within the breakline polygons and automatically classifies them as class 9, water. During this water classification routine, points that are within 1x NPS or less of the hydrographic features are moved to class 10, an ignored ground due to breakline proximity. Overage points are then identified in Terrascan and GeoCue is used to set the overlap bit for the overage points and the withheld bit is set on the withheld points previously identified in Terrascan before the ground classification routine was performed.

The lidar tiles were classified to the following classification schema:

- Class 1 = Unclassified, used for all other features that do not fit into the Classes 2, 7, 9, 10, 17, or 18, including vegetation, buildings, etc.
- Class 2 = Bare-Earth Ground
- Class 7 = Low Noise
- Class 9 = Water, points located within collected breaklines
- Class 10 = Ignored Ground due to breakline proximity
- Class 17 = Bridge Decks
- Class 18 = High Noise

After manual classification, the LAS tiles were peer reviewed and then underwent a final QA/QC. After the final QA/QC and corrections, all headers, appropriate point data records, and variable length records, including spatial reference information, are updated in GeoCue software and then verified using proprietary Dewberry tools.

Lidar Qualitative Assessment

Dewberry's qualitative assessment utilizes a combination of statistical analysis and interpretative methodology or visualization to assess the quality of the data for a bare-earth digital terrain model (DTM). This includes creating pseudo image products such as lidar orthos produced from the intensity returns, Triangular Irregular Network (TIN)'s, Digital Elevation Models (DEM) and 3-dimensional models as well as reviewing the actual point cloud data. This process looks for anomalies in the data, areas where man-made structures or vegetation points may not have been classified properly to produce a bare-earth model, and other classification errors. This report will present representative examples where the lidar and post processing had issues as well as examples of where the lidar performed well.

VISUAL REVIEW

The following sections describe common types of issues identified in lidar data and the results of the visual review for Texas Red River FEMA R6 lidar project.

Data Voids

The LAS files are used to produce density grids using the commercial software package QT Modeler (QTM) which creates a 3-dimensional data model derived from Class 2 (ground) points in the LAS files. Grid spacing is based on the project density deliverable requirement for un-obscured areas. Acceptable voids (areas with no lidar returns in the LAS files) that are present in the majority of lidar projects include voids caused by bodies of water. No unacceptable voids are present in the Texas Red River FEMA R6 lidar project.

Artifacts

Artifacts are caused by the misclassification of ground points and usually represent vegetation and/or man-made structures. The artifacts identified are usually low lying structures, such as porches or low vegetation used as landscaping in neighborhoods and other developed areas. These low lying features are extremely difficult for the automated algorithms to detect as non-ground and must be removed manually. The vast majority of these features have been removed but a small number of these features are still in the ground classification. The limited numbers of features remaining in the ground are usually 0.3 meters or less above the actual ground surface, and should not negatively impact the usability of the dataset.

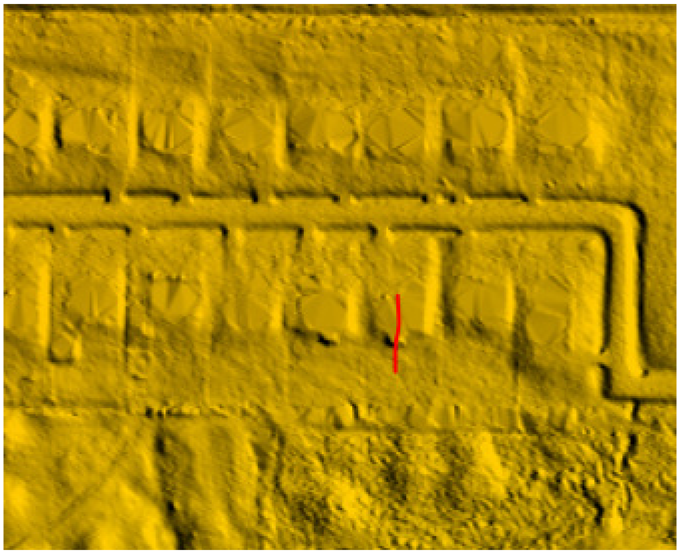

Figure 13 – Tile number 15SUS945900. Profile with points colored by class (class 1=white, class 2=orange) is shown in the top view and a TIN of the surface is shown in the bottom view. The red circle identifies a porch. A limited number of these small features are still classified as ground but do not impact the usability of the dataset.

Bridge Removal Artifacts

The DEM surface models are created from TINs or Terrains. TIN and Terrain models create continuous surfaces from the inputs. Because a continuous surface is being created, the TIN or Terrain will use interpolation to continue the surface beneath the bridge where no lidar data was acquired. Locations where bridges were removed will generally contain less detail in the bare-earth surface because these areas are interpolated.

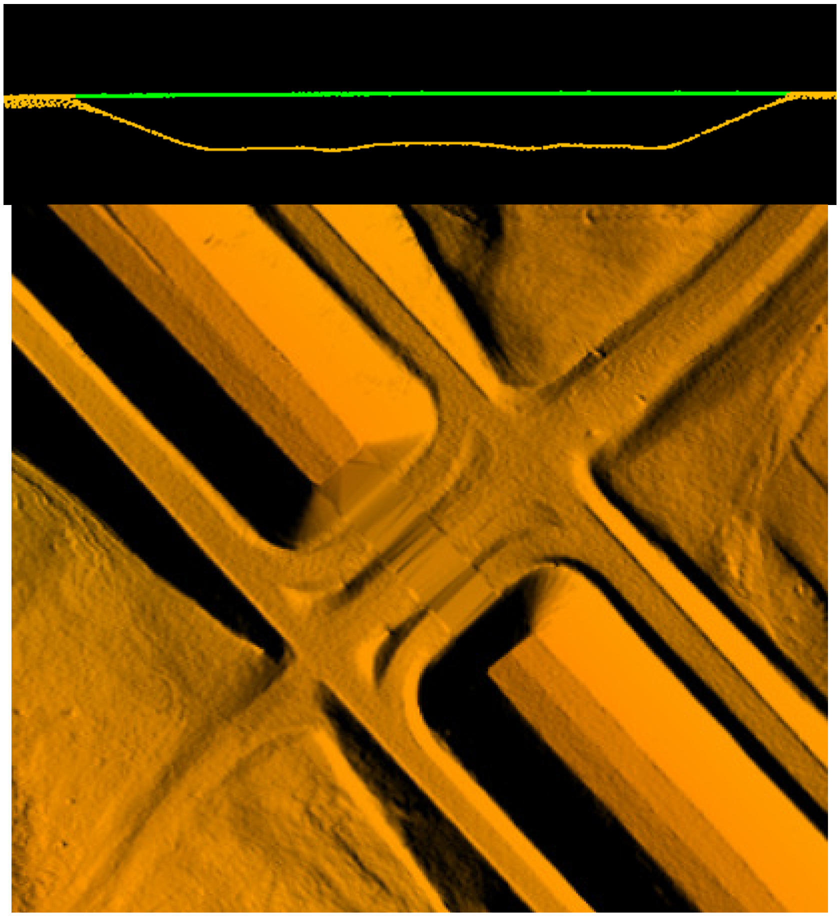

Figure 14 – Tile number 15SUS150660. The DEM in the bottom view shows an area where a bridge has been removed from ground. The surface model must make a continuous model and in order to do so, points are connected through interpolation. This results in less detail where the surface must be interpolated. The profile in the top view shows the lidar points of this particular feature colored by class. All bridge points have been removed from ground (orange) and are bridge deck (green).

Culverts and Bridges

Bridges have been removed from the bare earth surface while culverts remain in the bare earth surface. In instances where it is difficult to determine if the feature is a culvert or bridge, such as with some small bridges, Dewberry erred on assuming they would be culverts especially if they are on secondary or tertiary roads. Below is an example of a culvert that has been left in the ground surface.

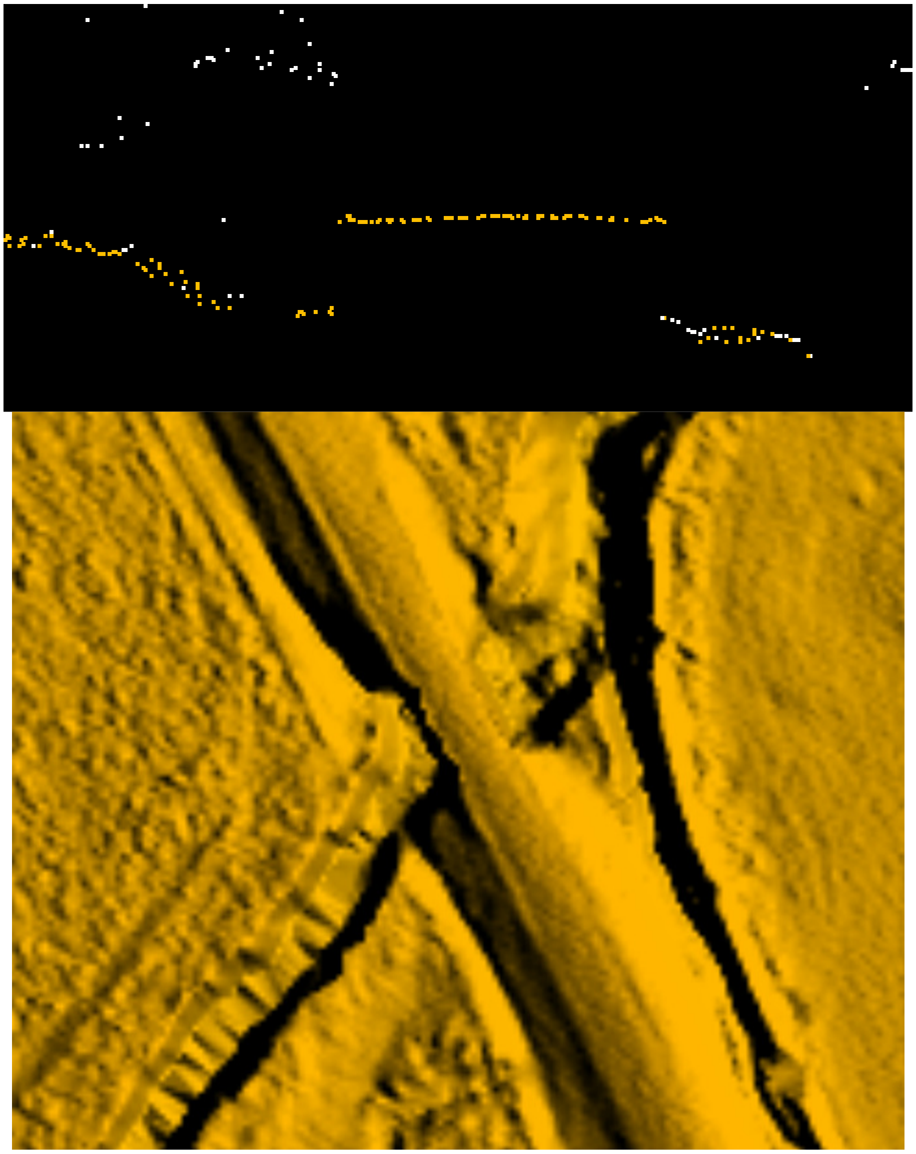

Figure 15– Tile number 15SUS120825. Profile with points colored by class (class 1=white, class 2=orange) is shown in the top view and the DEM is shown in the bottom view. This culvert remains in the bare earth surface. Bridges have been removed from the bare earth surface and classified to class 17.

Dirt Mounds

Irregularities in the natural ground exist and may be misinterpreted as artifacts that should be removed. Small hills and dirt mounds are present throughout the project area. These features are correctly included in the ground.

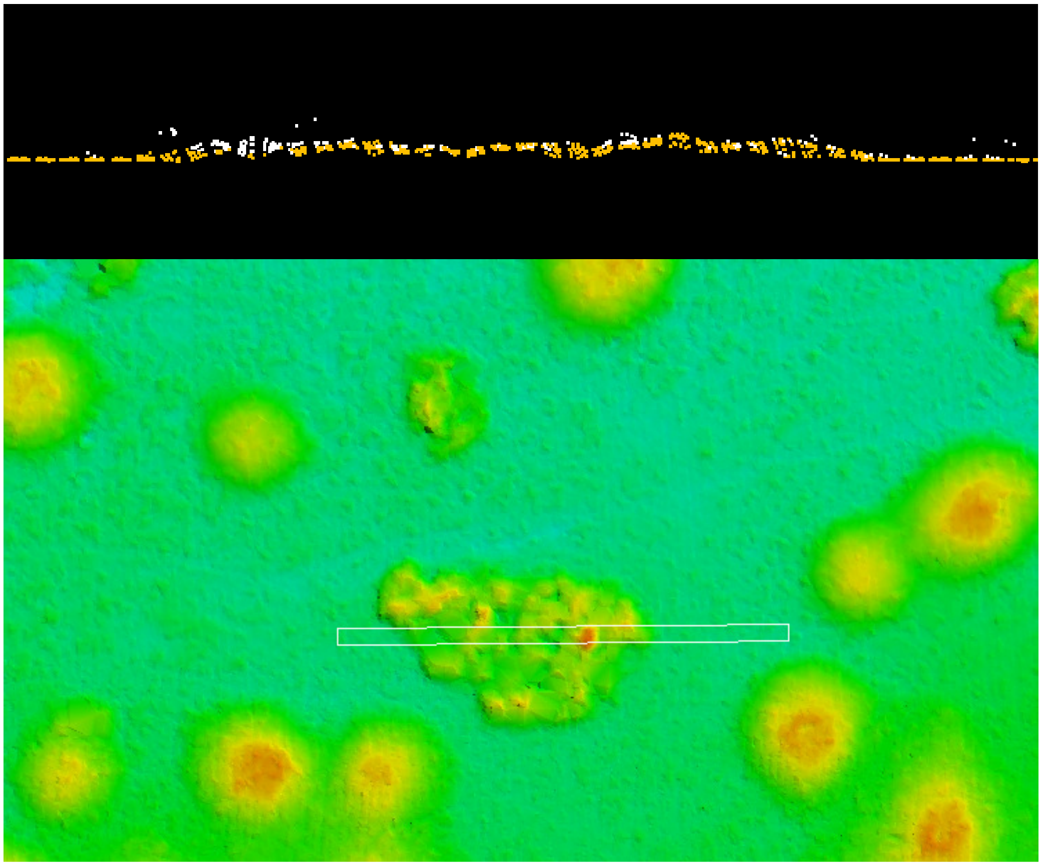

Figure 16 - 15SUS105900. Profile with the points colored by class (class 1=white, class 2=orange) is shown in the top view and a DEM of the surface is shown in the bottom view. These features are correctly included in the ground classification.

FORMATTING

After the final QA/QC is performed and all corrections have been applied to the dataset, all lidar files are updated to the final format requirements and the final formatting, header information, point data records, and variable length records are verified using Dewberry proprietary tools. The table below lists some of the main lidar header fields that are updated and verified.

Classified Lidar Formatting		
Parameter	**Requirement**	**Pass/Fail**
LAS Version	1.4	Pass
Point Data Format	Format 6	Pass
Coordinate Reference System	NAD83 (2011) UTM Zone 15, meters and NAVD88 (Geoid 12B), meters in WKT Format	Pass
Global Encoder Bit	Should be set to 17 for Adjusted GPS Time	Pass
Time Stamp	Adjusted GPS Time (unique timestamps)	Pass
System ID	Should be set to the processing system/software and is set to NIIRS10 for GeoCue software	Pass
Multiple Returns	The sensor shall be able to collect multiple returns per pulse and the return numbers are recorded	Pass
Intensity	16 bit intensity values are recorded for each pulse	Pass
Classification	Required Classes include: Class 1: Unclassified Class 2: Ground Class 7: Low Noise Class 9: Water Class 10: Ignored Ground Class 17: Bridge Decks Class 18: High Noise	Pass
Overlap and Withheld Points	Overlap (Overage) and Withheld points are set to the Overlap and Withheld bits	Pass
Scan Angle	Recorded for each pulse	Pass
XYZ Coordinates	Unique Easting, Northing, and Elevation coordinates are recorded for each pulse	Pass

Lidar Positional Accuracy

BACKGROUND

Dewberry quantitatively tested the dataset by testing the vertical accuracy of the lidar. The vertical accuracy is tested by comparing the discreet measurement of the survey checkpoints to that of the interpolated value within the three closest lidar points that constitute the vertices of a three-dimensional triangular face of the TIN. Therefore, the end result is that only a small sample of the lidar data is actually tested. However there is an increased level of confidence with lidar data due to the relative accuracy. This relative accuracy in turn is based on how well one lidar point "fits" in comparison to the next contiguous lidar measurement, and is verified as part of the initial processing. If the relative accuracy of a dataset is within specifications and the dataset passes vertical accuracy requirements at the location of survey checkpoints, the vertical accuracy results can be applied to the whole dataset with high confidence due to the passing relative accuracy. Dewberry typically uses LP360 software to test the swath lidar vertical accuracy, Terrascan software to test the classified lidar vertical accuracy, and Esri ArcMap to test the DEM vertical accuracy so that three different software programs are used to validate the vertical accuracy for each project.

Dewberry also tests the horizontal accuracy of lidar datasets when checkpoints are photo-identifiable in the intensity imagery. Photo-identifiable checkpoints in intensity imagery typically include checkpoints located at the ends of paint stripes on concrete or asphalt surfaces or checkpoints located at 90 degree corners of different reflectivity, e.g. a sidewalk corner adjoining a grass surface. The XY coordinates of checkpoints, as defined in the intensity imagery, are compared to surveyed XY coordinates for each photo-identifiable checkpoint. These differences are used to compute the tested horizontal accuracy of the lidar. As not all projects contain photo-identifiable checkpoints, the horizontal accuracy of the lidar cannot always be tested.

SURVEY VERTICAL ACCURACY CHECKPOINTS

For the vertical accuracy assessment, two hundred fifty (250) check points were surveyed for the project and are located within bare earth/open terrain, grass/weeds/crops, and forested/fully grown land cover categories. Please see the separate survey report included with the full project deliverables which details and validates how the survey was completed for this project.

Checkpoints were evenly distributed throughout the project area so as to cover as many flight lines as possible using the “dispersed method” of placement.

All checkpoints surveyed for vertical accuracy testing purposes are listed in the following table.

Point ID	NAD83(2011) UTM Zone 15		NAVD88 (Geoid 12B)
	Easting X (m)	Northing Y (m)	Elevation (m)
NVA-145	346371.838	3542829.583	119.695
NVA-146	360768.233	3542867.262	104.760
NVA-147	370500.930	3544415.239	90.220
NVA-148	388116.412	3540429.608	78.330
NVA-149	398060.759	3551679.816	90.999

NVA-150	379884.025	3552515.847	83.829
NVA-151	369271.247	3551081.148	102.192
NVA-152	360863.125	3552319.357	117.673
NVA-153	348277.153	3552820.772	115.439
NVA-154	342140.761	3558701.184	125.572
NVA-155	355613.409	3557836.841	114.241
NVA-156	370980.522	3559004.204	93.889
NVA-157	389931.941	3560926.636	97.271
NVA-158	399870.602	3568374.475	93.153
NVA-159	378347.796	3569854.846	64.015
NVA-160	362541.783	3568838.635	100.881
NVA-161	347478.289	3570697.210	130.663
NVA-162	334616.559	3563083.036	130.087
NVA-163	325435.263	3568275.399	127.316
NVA-164	313636.461	3573534.912	164.383
NVA-165	336534.253	3576070.030	104.166
NVA-166	357436.839	3576226.948	101.318
NVA-167	372523.267	3575888.679	68.572
NVA-168	392137.544	3576602.341	90.641
NVA-169	400537.991	3582053.121	105.286
NVA-170	390552.161	3589819.132	117.957
NVA-171	380144.514	3584615.114	99.457
NVA-172	374181.644	3589648.799	99.177
NVA-173	363312.667	3583217.848	73.358
NVA-174	348957.335	3582332.664	88.291
NVA-175	329772.235	3582727.708	123.538
NVA-176	323434.292	3584779.216	109.803
NVA-177	312253.166	3583811.180	119.455
NVA-178	316052.985	3596516.079	124.546
NVA-179	332157.715	3596934.185	115.057
NVA-180	349694.639	3591040.019	101.898
NVA-181	361557.021	3593792.117	112.020
NVA-182	372760.269	3602026.231	104.732
NVA-183	387349.087	3597463.997	109.186
NVA-184	396361.263	3605052.673	94.315
NVA-185	383279.018	3607282.798	81.727
NVA-186	363451.924	3607212.967	111.192
NVA-187	350095.812	3603764.595	110.234
NVA-188	337541.998	3605376.246	130.596
NVA-189	325193.139	3605371.020	123.725
NVA-190	322544.973	3614855.177	111.597
NVA-191	336274.615	3618335.356	80.821
NVA-192	354193.082	3615649.530	94.174
NVA-193	374033.560	3615293.525	91.568
NVA-194	389597.058	3613708.986	84.389
NVA-195	399449.012	3619287.080	75.773
NVA-196	388712.480	3623590.764	60.956

NVA-197	373391.663	3626563.299	66.803
NVA-198	353442.587	3624748.404	87.617
NVA-199	339123.284	3630482.038	93.800
NVA-200	318058.248	3622895.244	111.184
NVA-201	305011.375	3625541.220	144.548
NVA-202	278112.263	3637707.801	144.681
NVA-203	292615.264	3636133.620	180.066
NVA-204	309228.941	3634184.323	130.749
NVA-205	325877.152	3632191.954	131.826
NVA-206	358439.158	3634420.877	104.594
NVA-207	372049.972	3635173.645	99.852
NVA-208	390140.675	3631236.806	71.697
NVA-209	397963.623	3642720.704	89.114
NVA-210	388852.829	3641722.121	78.899
NVA-211	372125.274	3642853.923	117.964
NVA-212	353465.874	3645261.929	77.982
NVA-213	340098.208	3645476.996	90.334
NVA-214	327035.515	3638502.360	101.360
NVA-215	325640.097	3646938.029	88.704
NVA-216	317398.016	3646419.013	113.526
NVA-217	303061.117	3642373.239	132.379
NVA-218	298076.201	3647595.183	132.427
NVA-219	285822.030	3648925.306	159.009
NVA-220	288097.773	3660187.483	147.717
NVA-221	310360.672	3658525.893	119.397
NVA-222	327640.686	3665124.007	111.753
NVA-223	340431.052	3657625.674	111.986
NVA-224	371553.123	3655501.892	126.703
NVA-225	387677.970	3655835.872	109.066
NVA-226	401666.864	3655693.625	90.967
NVA-227	392226.758	3664390.914	79.104
NVA-228	380141.520	3669183.551	116.147
NVA-229	358215.082	3668550.679	120.600
NVA-230	338672.597	3671682.237	114.583
NVA-231	316315.879	3669606.113	114.456
NVA-232	292896.922	3674139.166	145.179
NVA-233	290649.500	3691384.002	117.339
NVA-234	306589.946	3684860.207	105.251
NVA-235	329845.567	3682162.913	95.347
NVA-236	344140.946	3675904.647	117.490
NVA-237	356906.107	3675901.398	105.594
NVA-238	373787.896	3673628.637	119.597
NVA-239	396153.352	3680887.361	79.557
NVA-240	400874.360	3694963.604	81.564
NVA-241	383010.494	3691947.879	86.902
NVA-242	377517.586	3685944.306	86.141
NVA-243	364992.065	3688513.455	90.968

NVA-244	361865.496	3697182.279	100.351
NVA-245	350439.281	3691154.437	83.203
NVA-246	343547.608	3701256.043	112.263
NVA-247	340589.307	3689574.875	85.899
NVA-248	331537.517	3699594.530	95.957
NVA-249	317724.532	3687016.458	98.161
NVA-250	315728.256	3699758.737	101.348
NVA-251	308090.210	3692802.993	105.664
NVA-252	297591.245	3701258.322	106.602
NVA-253	280387.004	3701101.986	119.077
NVA-254	277899.191	3710898.517	140.231
NVA-255	294152.824	3707044.538	140.922
NVA-256	309539.149	3709274.657	97.608
NVA-257	324274.886	3711359.845	118.951
NVA-258	351012.210	3707939.821	123.708
NVA-259	363315.121	3704706.346	121.847
NVA-260	380069.865	3704289.773	109.651
NVA-261	389253.864	3709884.451	86.115
NVA-262	401074.765	3703907.268	115.362
NVA-263	363023.068	3711470.917	104.286
NVA-264	353284.921	3716407.097	109.588
NVA-265	334503.103	3713658.032	145.128
NVA-266	321799.230	3718053.716	123.520
NVA-267	307693.439	3720408.111	126.410
NVA-268	291501.056	3721504.352	142.868
NVA-269	275091.935	3720386.618	150.448
NVA-270	279200.596	3726976.842	160.065
NVA-271	299680.708	3726890.125	145.125
NVA-272	318055.771	3726040.401	141.483
NVA-273	331597.242	3726223.070	117.822
NVA-274	345934.057	3719979.515	115.147
NVA-275	361284.870	3720629.392	95.313
NVA-276	333127.735	3730647.438	104.409
NVA-277	321360.821	3735211.058	120.852
NVA-278	309562.601	3734493.575	127.566
NVA-279	292388.593	3735533.164	151.828
NVA-280	282056.722	3742187.112	142.133
NVA-281	298710.583	3745732.828	142.701
NVA-282	310032.988	3741347.174	125.636
NVA-283	330774.578	3740802.180	108.087
NVA-284	339828.578	3735820.980	105.740
NVA-285	354342.474	3734076.386	115.697
NVA-286	358457.754	3750024.036	120.741
NVA-287	344018.148	3754269.122	125.520
NVA-288	334623.300	3752051.897	148.317
NVA-289	312281.663	3752178.058	116.450
NVA-290	299217.379	3763982.770	172.933

NVA-291	320446.379	3758719.946	149.886
NVA-292	339283.937	3764254.225	130.466
VVA-101	346963.842	3548154.938	113.551
VVA-102	357539.919	3547564.496	108.558
VVA-103	372854.526	3548318.241	90.113
VVA-104	383720.916	3544788.897	93.166
VVA-105	392637.609	3548750.997	58.603
VVA-106	395691.785	3557417.224	91.537
VVA-107	378390.174	3557891.973	70.727
VVA-108	362689.140	3560861.742	87.908
VVA-109	343653.040	3560807.995	109.409
VVA-110	331135.217	3568274.217	121.428
VVA-111	350255.367	3570068.111	113.025
VVA-112	368093.341	3568339.186	90.535
VVA-113	379303.055	3572006.247	65.122
VVA-114	393863.590	3568198.274	95.172
VVA-115	397137.929	3579892.910	95.259
VVA-116	385630.005	3579314.135	86.372
VVA-117	365522.105	3577979.711	75.521
VVA-118	354637.339	3580745.028	95.454
VVA-119	340003.533	3578704.184	105.531
VVA-120	325934.856	3577772.490	126.093
VVA-121	313523.608	3580605.755	141.592
VVA-122	319434.413	3594518.728	79.692
VVA-123	338613.229	3589540.584	80.007
VVA-124	353563.062	3592716.588	103.513
VVA-125	369704.664	3590952.550	109.768
VVA-126	385845.229	3591269.292	103.413
VVA-127	397860.092	3599759.038	68.608
VVA-128	380099.307	3604687.951	114.863
VVA-129	362737.261	3603656.536	141.329
VVA-130	346292.759	3603936.557	105.890
VVA-131	327662.902	3604102.839	96.720
VVA-132	328324.037	3615170.966	107.293
VVA-133	343105.192	3613486.680	74.100
VVA-134	361966.156	3615553.931	89.874
VVA-135	386378.970	3612703.425	85.888
VVA-136	402147.361	3612140.521	58.951
VVA-137	394855.960	3627261.489	60.173
VVA-138	378205.383	3623406.225	62.122
VVA-139	360273.649	3624952.725	87.531
VVA-140	344064.880	3625117.867	119.825
VVA-141	321300.330	3629870.593	92.228
VVA-142	308302.465	3622298.024	100.867
VVA-143	301793.309	3631703.367	129.343
VVA-144	289660.102	3635433.163	173.789
VVA-145	278159.839	3640665.759	152.890

VVA-146	291742.237	3645021.523	162.436
VVA-147	309059.533	3645833.955	117.635
VVA-148	321990.326	3640207.792	132.501
VVA-149	341553.960	3642564.733	129.782
VVA-150	363444.164	3639224.435	109.374
VVA-151	378915.257	3635418.247	97.751
VVA-152	393049.806	3640326.918	60.504
VVA-153	393749.701	3654267.992	99.245
VVA-154	363739.864	3659191.310	110.562
VVA-155	336734.530	3663881.383	93.151
VVA-156	318831.849	3656966.988	111.658
VVA-157	290723.601	3655884.857	162.615
VVA-158	294989.011	3668424.991	153.292
VVA-159	311805.213	3674274.157	126.262
VVA-160	331792.561	3668126.201	97.295
VVA-161	351062.779	3671328.109	123.894
VVA-162	371746.375	3667551.309	106.542
VVA-163	399017.541	3667891.162	105.004
VVA-164	390929.669	3679203.210	102.281
VVA-165	369098.349	3679510.126	89.380
VVA-166	337540.940	3680851.115	90.730
VVA-167	322750.599	3681865.238	112.301
VVA-168	304082.759	3685573.529	105.788
VVA-169	290424.646	3679820.410	110.578
VVA-170	289374.604	3698830.564	115.352
VVA-171	307993.070	3698280.305	98.849
VVA-172	324161.317	3690455.538	93.099
VVA-173	342123.679	3697480.838	101.919
VVA-174	347169.755	3684464.861	86.432
VVA-175	367272.439	3696046.842	84.174
VVA-176	382457.264	3692289.818	85.098
VVA-177	392316.219	3710225.520	83.684
VVA-178	372487.997	3705229.045	116.298
VVA-179	357711.082	3709753.560	113.445
VVA-180	341762.919	3707771.159	118.753
VVA-181	329756.825	3711980.517	138.040
VVA-182	315211.884	3713285.225	110.537
VVA-183	297810.723	3712056.316	111.733
VVA-184	280243.092	3711952.076	143.861
VVA-185	275942.965	3723487.990	152.332
VVA-186	289225.899	3730476.000	155.349
VVA-187	308098.438	3730684.449	139.136
VVA-188	329991.862	3725864.780	119.238
VVA-189	350129.006	3722866.343	109.895
VVA-190	354168.688	3730693.844	100.479
VVA-191	346340.620	3738988.163	121.246
VVA-192	318338.055	3740658.177	122.373

VVA-193	298990.266	3738675.499	140.759
VVA-194	280159.556	3739257.088	155.604
VVA-195	295680.443	3752763.920	132.210
VVA-196	305581.078	3761941.160	134.963
VVA-197	316744.700	3754788.348	138.743
VVA-198	338258.657	3745477.929	131.777
VVA-199	358366.459	3743568.903	118.255
VVA-200	348862.914	3754865.735	117.671
VVA-201	356390.930	3762931.817	104.117
VVA-202	326480.904	3761122.833	108.419

Table 14: Texas Red River FEMA R6 surveyed accuracy checkpoints

The figure below shows the location of the QA/QC checkpoints used to test the positional accuracy of the dataset.

Texas Red River FEMA R6 Checkpoint Locations

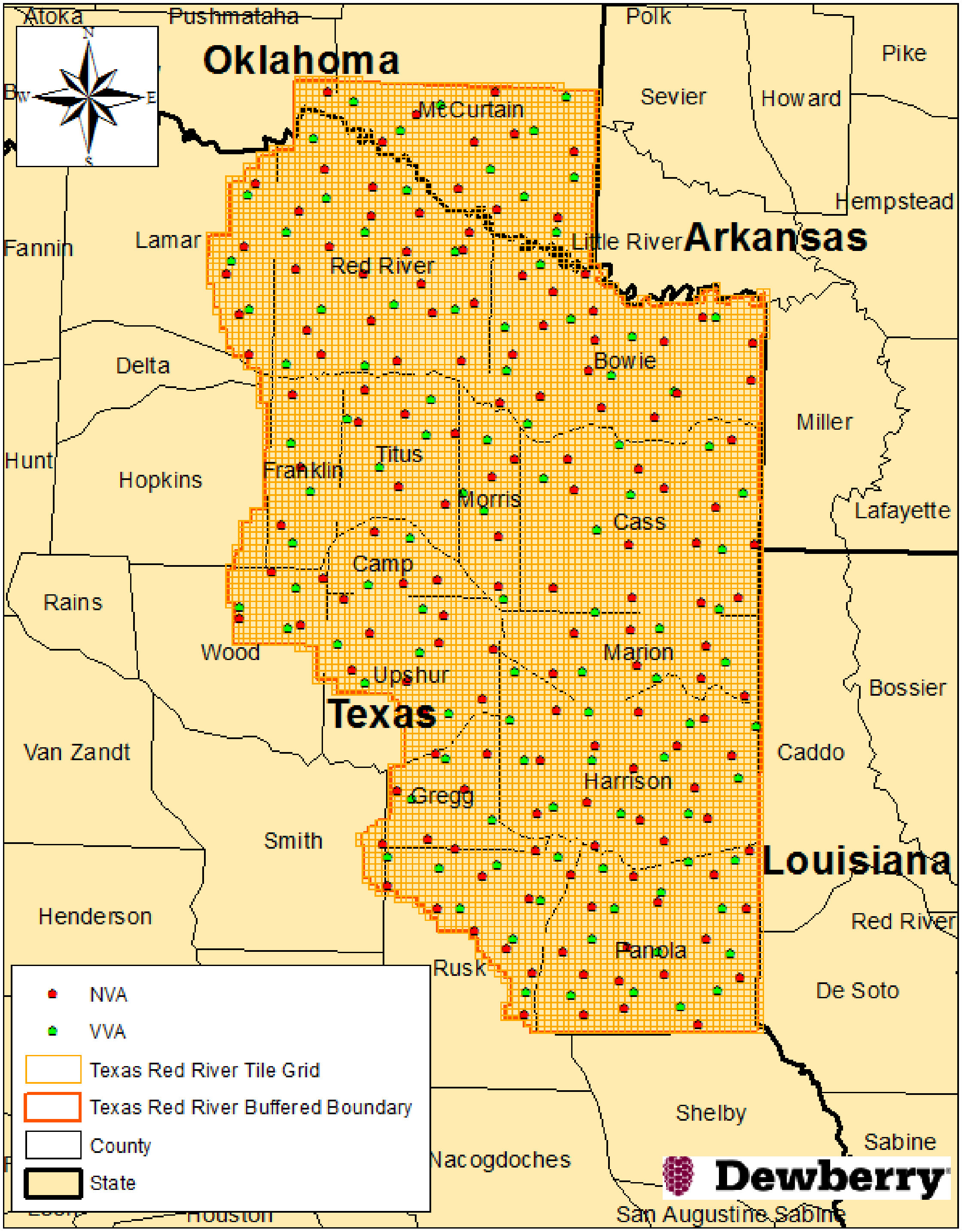

Figure 17 – Location of QA/QC Checkpoints

VERTICAL ACCURACY TEST PROCEDURES

NVA (Non-vegetated Vertical Accuracy) is determined with check points located only in non-vegetated terrain, including open terrain (grass, dirt, sand, and/or rocks) and urban areas, where there is a very high probability that the lidar sensor will have detected the bare-earth ground surface and where random errors are expected to follow a normal error distribution. The NVA determines how well the calibrated lidar sensor performed. With a normal error distribution, the vertical accuracy at the 95% confidence level is computed as the vertical root mean square error ($RMSE_z$) of the checkpoints x 1.9600. For the Texas Red River Lidar Project, vertical accuracy must be 19.6 cm or less based on an $RMSE_z$ of 10 cm x 1.9600.

VVA (Vegetated Vertical Accuracy) is determined with all checkpoints in vegetated land cover categories, including tall grass, weeds, crops, brush and low trees, and fully forested areas, where there is a possibility that the lidar sensor and post-processing may yield elevation errors that do not follow a normal error distribution. VVA at the 95% confidence level equals the 95th percentile error for all checkpoints in all vegetated land cover categories combined. The Texas Red River Lidar Project VVA standard is 29.4 cm based on the 95th percentile. The VVA is accompanied by a listing of the 5% outliers that are larger than the 95th percentile used to compute the VVA; these are always the largest outliers that may depart from a normal error distribution. Here, $Accuracy_z$ differs from VVA because $Accuracy_z$ assumes elevation errors follow a normal error distribution where RMSE procedures are valid, whereas VVA assumes lidar errors may not follow a normal error distribution in vegetated categories, making the RMSE process invalid.

The relevant testing criteria are summarized in Table 15.

Quantitative Criteria	Measure of Acceptability
Non-Vegetated Vertical Accuracy (NVA) in open terrain and urban land cover categories using $RMSE_z$ *1.9600	19.6 cm (based on $RMSE_z$ (10 cm) * 1.9600)
Vegetated Vertical Accuracy (VVA) in all vegetated land cover categories combined at the 95% confidence level	29.4 cm (based on combined 95th percentile)

Table 15 – Acceptance Criteria

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

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

VERTICAL ACCURACY RESULTS

The table below summarizes the tested vertical accuracy resulting from a comparison of the surveyed checkpoints to the elevation values present within the fully classified lidar LAS files.

Land Cover Category	# of Points	NVA – Non-vegetated Vertical Accuracy ($RMSE_z$ x 1.9600) Spec=19.6 cm	VVA – Vegetated Vertical Accuracy (95th Percentile) Spec=29.4 cm
NVA	148	10.9	
VVA	102		15.3

Table 16 – Tested NVA and VVA

This lidar dataset was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 10 cm RMSEz Vertical Accuracy Class. Actual NVA accuracy was found to be $RMSE_z$ =5.6 cm, equating to +/- 10.9 cm at 95% confidence level. Actual VVA accuracy was found to be +/- 15.3 cm at the 95th percentile.

The figure below illustrates the magnitude of the differences between the QA/QC checkpoints and lidar data. This shows that the majority of lidar elevations were within +/- 8 cm of the checkpoints elevations, but there were some outliers where lidar and checkpoint elevations differed by up to +27 cm.

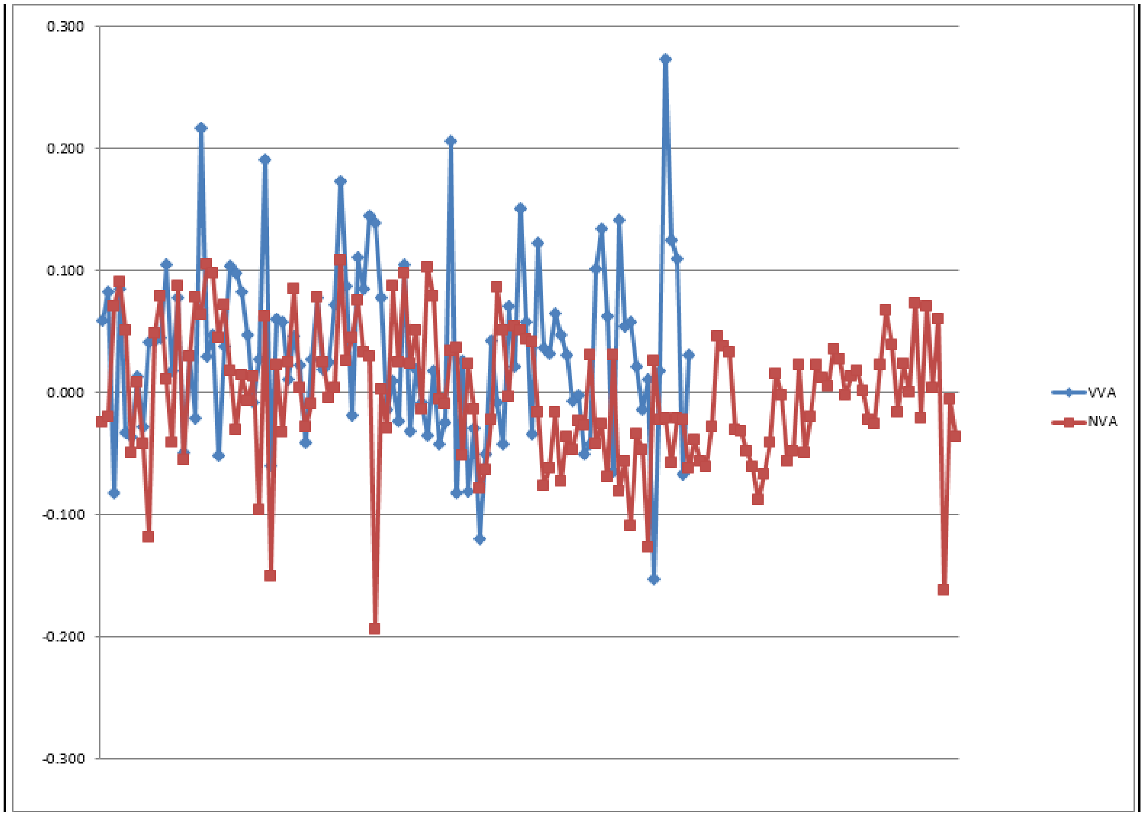

Figure 18 – Magnitude of elevation discrepancies per land cover category

Table 17 lists the 5% outliers that are larger than the VVA 95th percentile.

Point ID	NAD83(2011) UTM Zone 15		NAVD88 (Geoid 12B)	Lidar Z (m)	Delta Z	AbsDeltaZ
	Easting X (m)	Northing Y (m)	Survey Z (m)			
VVA-118	354637.339	3580745.028	95.454	95.670	0.216	0.216
VVA-129	362737.261	3603656.536	141.329	141.520	0.191	0.191
VVA-142	308302.465	3622298.024	100.867	101.040	0.173	0.173
VVA-161	351062.779	3671328.109	123.894	124.100	0.206	0.206
VVA-198	338258.657	3745477.929	131.777	132.050	0.273	0.273

Table 17 — 5% Outliers

Table 18 provides overall descriptive statistics.

100 % of Totals	# of Points	RMSEz (m) NVA Spec=0.1 m	Mean (m)	Median (m)	Skew	Std Dev (m)	Kurtosis	Min (m)	Max (m)
NVA	148	0.056	-0.001	-0.001	-0.431	0.056	0.508	-0.194	0.108
VVA	102	N/A	0.034	0.029	0.461	0.073	0.733	-0.153	0.273

Table 18 — Overall Descriptive Statistics

The figure below illustrates a histogram of the associated elevation discrepancies between the QA/QC checkpoints and elevations interpolated from the lidar triangulated irregular network (TIN). The frequency shows the number of discrepancies within each band of elevation differences. Although the discrepancies vary between a low of -0.19 meters and a high of +0.27 meters, the histogram shows that the majority of the discrepancies are skewed on the positive side. The vast majority of points are within the ranges of -0.075 meters to +0.075 meters.

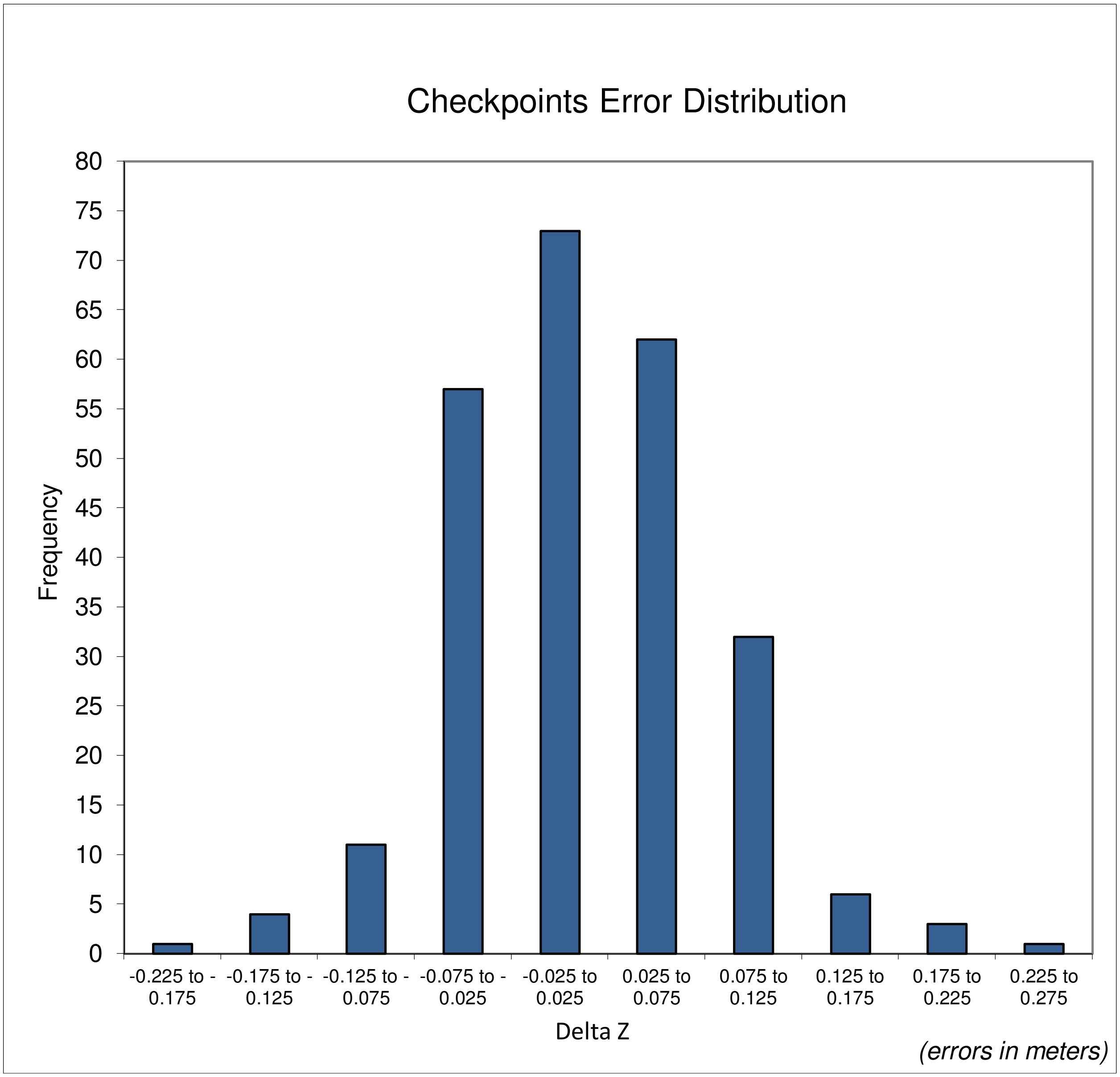

Figure 19 – Histogram of Elevation Discrepancies with errors in meters

Based on the vertical accuracy testing conducted by Dewberry, the lidar dataset for the Texas Red River FEMA R6 Lidar Project satisfies the project's pre-defined vertical accuracy criteria.

HORIZONTAL ACCURACY TEST PROCEDURES

Horizontal accuracy testing requires well-defined checkpoints that can be identified in the dataset. Elevation datasets, including lidar datasets, do not always contain well-defined checkpoints suitable for horizontal accuracy assessment. However, the ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) recommends at least half of the NVA vertical check points should be located at the ends of paint stripes or other point features visible on the lidar intensity image, allowing them to double as horizontal check points.

Dewberry reviews all NVA checkpoints to determine which, if any, of these checkpoints are located on photo-identifiable features in the intensity imagery. This subset of checkpoints are then used for horizontal accuracy testing.

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

1. Dewberry's team surveyed QA/QC vertical checkpoints in accordance with the project's specifications and tried to locate half of the NVA checkpoints on features photo-identifiable in the intensity imagery.
2. Next, Dewberry identified the well-defined features in the intensity imagery.
3. Dewberry then computed the associated xy-value differences between the coordinates of the well-defined feature in the lidar intensity imagery and the ground truth survey checkpoints.
4. The data were analyzed by Dewberry to assess the accuracy of the data. Horizontal accuracy was assessed using NSSDA methodology where horizontal accuracy is calculated at the 95% confidence level. This report provides the results of the horizontal accuracy testing.

HORIZONTAL ACCURACY RESULTS

Five checkpoints were determined to be photo-identifiable in the intensity imagery and were used to test the horizontal accuracy of the lidar dataset. As only five (5) checkpoints were photo-identifiable, the results are not statistically significant enough to report as a final tested value, but the results of the testing are still shown in the Table below.

Using NSSDA methodology (endorsed by the ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014)), horizontal accuracy at the 95% confidence level (called ACCURACYr) is computed by the formula RMSEr * 1.7308 or RMSExy * 2.448.

No horizontal accuracy requirements or thresholds were provided for this project. However, lidar datasets are generally calibrated by methods designed to ensure a horizontal accuracy of 1 meter or less at the 95% confidence level.

# of Points	$RMSE_x$ (Target=41 cm)	$RMSE_y$ (Target=41 cm)	$RMSE_r$ (Target=58 cm)	$ACCURACY_r$ ($RMSE_r$ x 1.7308) Target=100 cm
5	39.4	20.3	44.3	76.8

Table 19-Tested horizontal accuracy at the 95% confidence level

This data set was produced to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 41 cm RMSEx/RMSEy Horizontal Accuracy Class which equates to Positional Horizontal Accuracy = +/- 1 meter at a 95% confidence level. Five (5) checkpoints were photo-identifiable but do not produce a statistically significant tested horizontal accuracy value. Using this small sample set of photo-identifiable checkpoints, positional accuracy of this dataset was found to be RMSEx = 39.4 cm and RMSEy = 20.3 cm which equates to +/- 76.8 cm at 95%

confidence level. While not statistically significant, the results of the small sample set of checkpoints are within the produced to meet horizontal accuracy.

Breakline Production & Qualitative Assessment Report

BREAKLINE PRODUCTION METHODOLOGY

Dewberry used GeoCue software to develop lidar stereo models of the project area so the lidar derived data could be viewed in 3-D stereo using Socet Set softcopy photogrammetric software. Using lidargrammetry procedures with lidar intensity imagery, Dewberry used the stereo models to stereo-compile the two types of hydrographic breaklines in accordance with the project's Data Dictionary. Kinetics used LP360 and intensity imagery to collect the Lakes and Ponds and Rivers and Streams for a portion of the project in accordance with the project's Data Dictionary.

All drainage breaklines are monotonically enforced to show downhill flow. Water bodies are at a constant elevation where the lowest elevation of the water body has been applied to the entire water body.

BREAKLINE QUALITATIVE ASSESSMENT

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

Completeness and horizontal placement is verified through visual reviews against lidar intensity imagery. Automated checks are applied on all breakline features to validate topology, including the 3D connectivity of features, enforced monotonicity on linear hydrographic breaklines, and flatness on water bodies.

The next step is to compare the elevation of the breakline vertices against the ground elevation extracted from the ESRI Terrain built from the lidar ground points, keeping in mind that a discrepancy is expected because of the hydro-enforcement applied to the breaklines and because of the interpolated imagery used to acquire the breaklines. A given tolerance is used to validate if the elevations differ too much from the lidar.

After all corrections and edits to the breakline features, the breaklines are imported into the final GDB and verified for correct formatting.

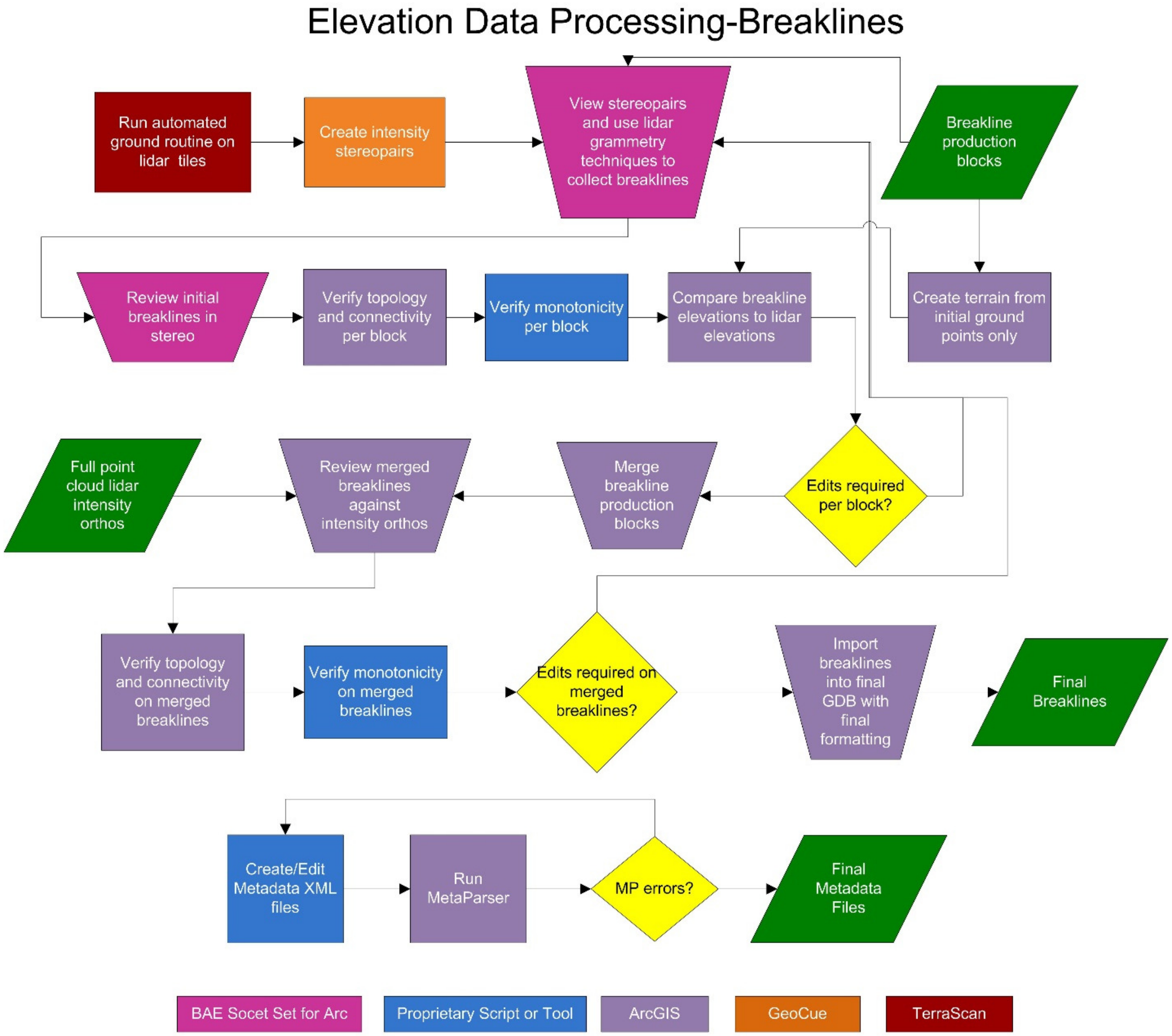

Figure 20-Breakline QA/QC workflow

BREAKLINE CHECKLIST

The following table represents a portion of the high-level steps in Dewberry's Production and QA/QC checklist that were performed for this project.

Pass/Fail	Validation Step
Pass	Use lidar-derived data, which may include intensity imagery, stereo pairs, bare earth ground models, density models, slope models, and terrains, to collect breaklines according to project specifications.
Pass	In areas of heavy vegetation or where the exact shoreline is hard to delineate, it is better to err on placing the breakline *slightly* inside or seaward of the shoreline (breakline can be inside shoreline by 1x-2x NPS).

Pass	After each producer finishes breakline collection for a block, each producer must perform a completeness check, breakline variance check, and all automated checks on their block before calling that block complete and ready for the final merge and QC
Pass	After breaklines are completed for production blocks, all production blocks should be merged together and completeness and automated checks should be performed on the final, merged GDB. Ensure correct snapping-horizontal (x,y) and vertical (z)-between all production blocks.
Pass	Check entire dataset for missing features that were not captured, but should be to meet baseline specifications or for consistency. Features should be collected consistently across tile bounds. Check that the horizontal placement of breaklines is correct. Breaklines should be compared to full point cloud intensity imagery and terrains
Pass	Breaklines are correctly edge-matched to adjoining datasets in completion, coding, and horizontal placement.
Pass	Using a terrain created from lidar ground (all ground including 2, 8, and 10) and water points (class 9), compare breakline Z values to interpolated lidar elevations.
Pass	Perform all Topology and Data Integrity Checks
Pass	Perform hydro-flattening and hydro-enforcement checks including monotonicity and flatness from bank to bank on linear hydrographic features and flatness of water bodies. Tidal waters should preserve as much ground as possible and can include variations or be non-monotonic.

Table 20-A subset of the high-level steps from Dewberry's Production and QA/QC checklist performed for this project.

DATA DICTIONARY

The following data dictionary was used for this project.

Horizontal and Vertical Datum

The horizontal datum shall be North American Datum of 1983(2011), Units in Meters. The vertical datum shall be referenced to the North American Vertical Datum of 1988 (NAVD 88), Units in Meters. Geoid12B shall be used to convert ellipsoidal heights to orthometric heights.

Coordinate System and Projection

All data shall be projected to UTM Zone 15, Horizontal Units in Meters and Vertical Units in Meters.

Inland Streams and Rivers

Feature Dataset: BREAKLINES
Feature Type: Polygon
Contains Z Values: Yes
XY Resolution: Accept Default Setting
XY Tolerance: 0.003

Feature Class: STREAMS_AND_RIVERS
Contains M Values: No
Annotation Subclass: None
Z Resolution: Accept Default Setting
Z Tolerance: 0.001

Description

This polygon feature class will depict linear hydrographic features with a width greater than 100 feet.

Table Definition

Field Name	Data Type	Allow Null Values	Default Value	Domain	Precision	Scale	Length	Responsibility
OBJECTID	Object ID							Assigned by Software

SHAPE	Geometry							Assigned by Software
SHAPE_LENGTH	Double	Yes			0	0		Calculated by Software
SHAPE_AREA	Double	Yes			0	0		Calculated by Software

Feature Definition

Description	Definition	Capture Rules
Streams and Rivers	Linear hydrographic features such as streams, rivers, canals, etc. with an average width greater than 100 feet. In the case of embankments, if the feature forms a natural dual line channel, then capture it consistent with the capture rules. Other natural or manmade embankments will not qualify for this project.	Capture features showing dual line (one on each side of the feature). Average width shall be greater than 100 feet to show as a double line. Each vertex placed should maintain vertical integrity. Generally both banks shall be collected to show consistent downhill flow. There are exceptions to this rule where a small branch or offshoot of the stream or river is present. The banks of the stream must be captured at the same elevation to ensure flatness of the water feature. If the elevation of the banks appears to be different see the task manager or PM for further guidance. Breaklines must be captured at or just below the elevations of the immediately surrounding terrain. Under no circumstances should a feature be elevated above the surrounding lidar points. Acceptable variance in the negative direction will be defined for each project individually. These instructions are only for docks or piers that follow the coastline or water's edge, not for docks or piers that extend perpendicular from the land into the water. If it can be reasonably determined where the edge of water most probably falls, beneath the dock or pier, then the edge of water will be collected at the elevation of the water where it can be directly measured. If there is a clearly-indicated headwall or bulkhead adjacent to the dock or pier and it is evident that the waterline is most probably adjacent to the headwall or bulkhead, then the water line will follow the headwall or bulkhead at the elevation of the water where it can be directly measured. If there is no clear indication of the location of the water's edge beneath the dock or pier, then the edge of water will follow the outer edge of the dock or pier as it is adjacent to the water, at the measured elevation of the water. Every effort should be made to avoid breaking a stream or river into segments. Dual line features shall break at road crossings (culverts). In areas where a bridge is present the dual line feature shall continue through the bridge. Islands: The double line stream shall be captured around an island if the island is greater than 1 acre. In this case a segmented polygon shall be used around the island in order to allow for the island feature to remain as a "hole" in the feature.

Inland Ponds and Lakes

Feature Dataset: BREAKLINES
Feature Type: Polygon
Contains Z Values: Yes
XY Resolution: Accept Default Setting
XY Tolerance: 0.003

Feature Class: PONDS_AND_LAKES
Contains M Values: No
Annotation Subclass: None
Z Resolution: Accept Default Setting
Z Tolerance: 0.001

Description

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

Table Definition

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

Feature Definition

Description	Definition	Capture Rules
Ponds and Lakes	Land/Water boundaries of constant elevation water bodies such as lakes, reservoirs, ponds, etc. Features shall be defined as closed polygons and contain an elevation value that reflects the best estimate of the water elevation at the time of data capture. Water body features will be captured for features 2 acres in size or greater. “Donuts” will exist where there are islands within a closed water body feature.	Water bodies shall be captured as closed polygons with the water feature to the right. The compiler shall take care to ensure that the z-value remains consistent for all vertices placed on the water body. Breaklines must be captured at or just below the elevations of the immediately surrounding terrain. Under no circumstances should a feature be elevated above the surrounding lidar points. Acceptable variance in the negative direction will be defined for each project individually. An Island within a Closed Water Body Feature that is 1 acre in size or greater will also have a “donut polygon” compiled. These instructions are only for docks or piers that follow the coastline or water’s edge, not for docks or piers that extend perpendicular from the land into the water. If it can be reasonably determined where the edge of water most probably falls, beneath the dock or pier, then the edge of water will be collected at the elevation of the water where it can be directly measured. If there is a clearly-indicated headwall or bulkhead adjacent to the dock or pier and it is evident that the waterline is most probably adjacent to the headwall or bulkhead, then the water line will follow the headwall or bulkhead at the elevation of the water where it can be directly measured.

		If there is no clear indication of the location of the water's edge beneath the dock or pier, then the edge of water will follow the outer edge of the dock or pier as it is adjacent to the water, at the measured elevation of the water.

Beneath Bridge Saddle Breaklines

Feature Dataset: BREAKLINES
Feature Type: Polyline
Contains Z Values: Yes
XY Resolution: Accept Default Setting
XY Tolerance: 0.003

Feature Class: Bridge_Breaklines
Contains M Values: No
Annotation Subclass: None
Z Resolution: Accept Default Setting
Z Tolerance: 0.001

Description

This polyline feature class is used to enforce terrain beneath bridge decks where ground data may not have been acquired. Enforcing the terrain beneath bridge decks prevents bridge saddles.

Table Definition

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

Feature Definition

Description	Definition	Capture Rules
Bridge Breaklines	Bridge Breaklines should be used where necessary to enforce terrain beneath bridge decks and to prevent bridge saddles in the bare earth DEMs.	Bridge breaklines should be collected beneath bridges where bridge saddles exist or are likely to exist in the bare earth DEMs. Bridge breaklines should be collected perpendicular to the bridge deck so that the endpoints are on either side of the bridge deck. Typically two bridge breaklines are collected per bridge deck, one at either end of the bridge deck to enforce the terrain under the full bridge deck. The endpoints of the bridge breaklines will match the elevation of the ground at their xy position to enforce the ground/bare earth elevations beneath the bridge deck and prevent bridge saddles from forming.

DEM Production & Qualitative Assessment

DEM PRODUCTION METHODOLOGY

Dewberry utilized ESRI software and Global Mapper for the DEM production and QC process. ArcGIS software is used to generate the products and the QC is performed in both ArcGIS and Global Mapper. The figure below shows the entire process necessary for bare earth DEM production, starting from the lidar swath processing.

The final bare-earth lidar points are used to create a terrain. The final 3D breaklines collected for the project are also enforced in the terrain. The terrain is then converted to raster format using linear interpolation. For most projects, a single terrain/DEM can be created for the whole project. For very large projects, multiple terrains/DEMs may be created. The DEM(s) is reviewed for any issues requiring corrections, including remaining lidar mis-classifications, erroneous breakline elevations, poor hydro-flattening or hydro-enforcement, and processing artifacts. After corrections are applied, the DEM(s) is then split into individual tiles following the project tiling scheme. The tiles are verified for final formatting and then loaded into Global Mapper to ensure no missing or corrupt tiles and to ensure seamlessness across tile boundaries.

Figure 21-DEM Production Workflow

DEM QUALITATIVE ASSESSMENT

Dewberry performed a comprehensive qualitative assessment of the bare earth DEM deliverables to ensure that all tiled DEM products were delivered with the proper extents, were free of processing artifacts, and contained the proper referencing information. This process was performed in ArcGIS software with the use of a tool set Dewberry has developed to verify that the raster extents match those of the tile grid and contain the correct projection information. The DEM data was reviewed at a scale of 1:5000 to review for artifacts caused by the DEM generation process and to review the hydro-flattened features. To perform this review Dewberry creates HillShade models and overlays a partially transparent colorized elevation model to review for these issues. All corrections are completed using Dewberry's proprietary correction workflow. Upon completion of the corrections, the DEM data is loaded into Global Mapper for its second review and to verify corrections. Once the DEMs are tiled out, the final tiles are again loaded into Global Mapper to ensure coverage, extents, and that the final tiles are seamless.

The images below show an example of a bare earth DEM tile.

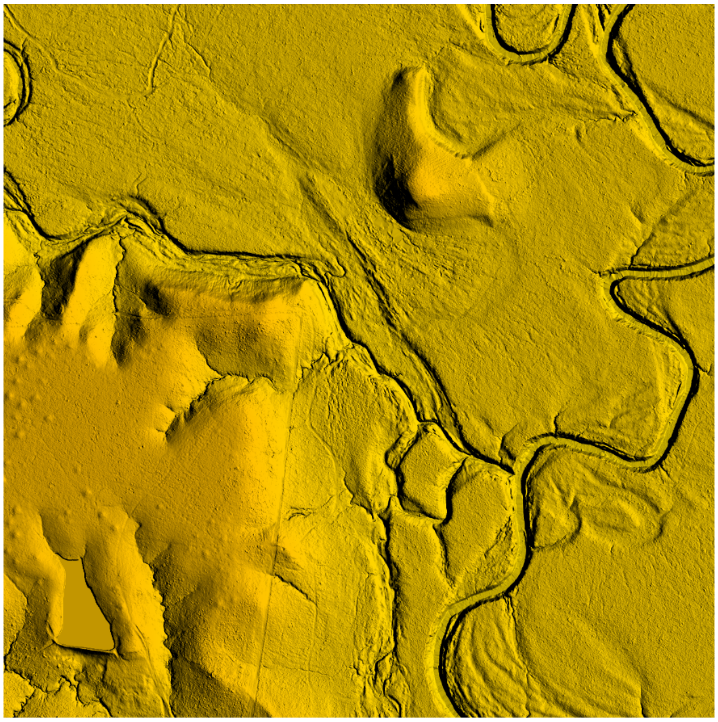

Figure 22-Tile Name 15SUS330885. The bare earth DEM is shown above

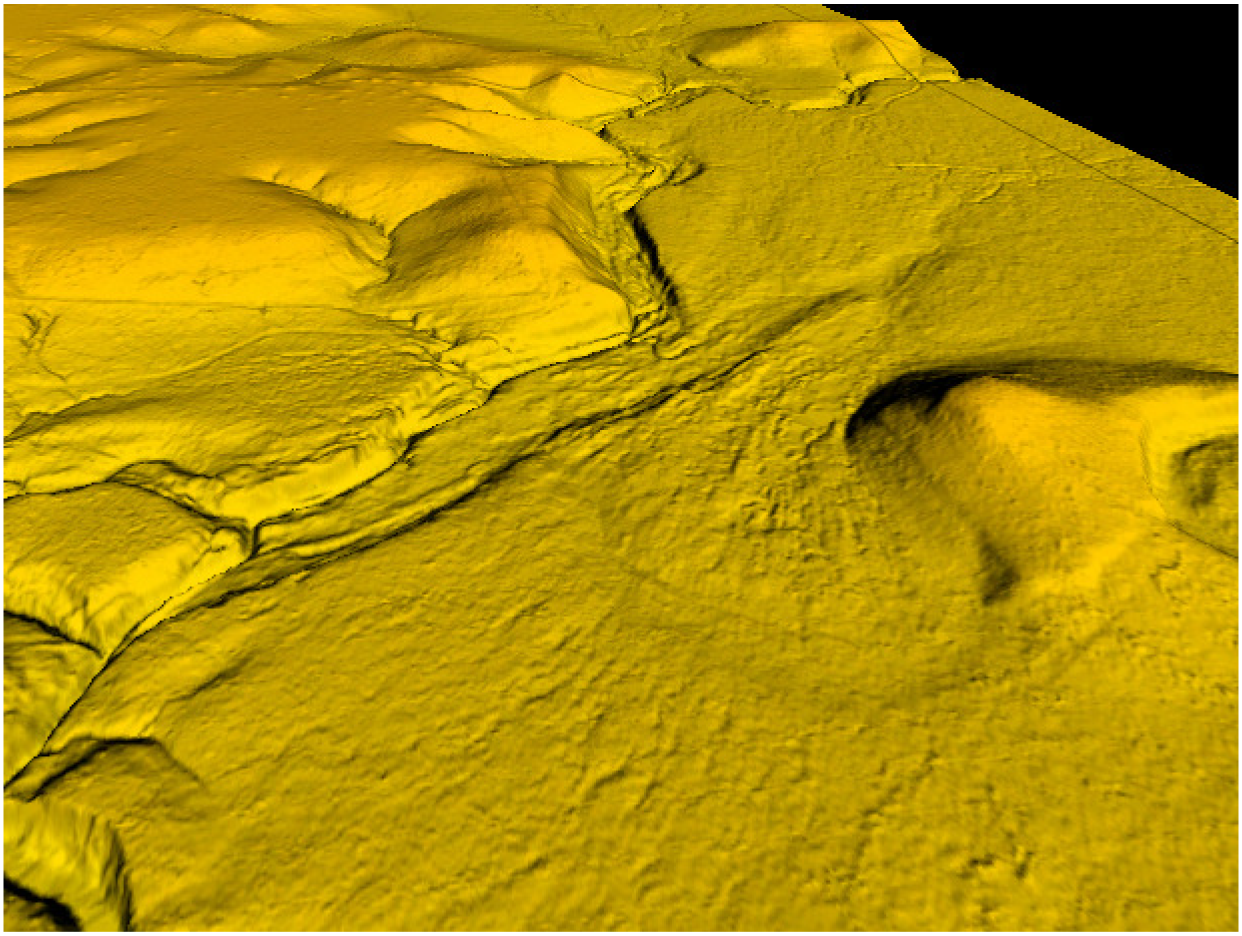

Figure 23- Tile Name 15SUS330885. 3D Profile view of the bare earth DEM

When some bridges are removed from the ground surface, the distance from bridge abutment to bridge abutment is small enough that the DEM interpolates across the entire bridge opening, forming 'bridge saddles.' Dewberry collected 3D bridge breaklines in locations where bridge saddles were present and enforced these breaklines in the final DEM creation to help mitigate the bridge saddle artifacts. The image below on the left shows a bridge saddle while the image below on the right shows the same bridge after bridge breaklines have been enforced.

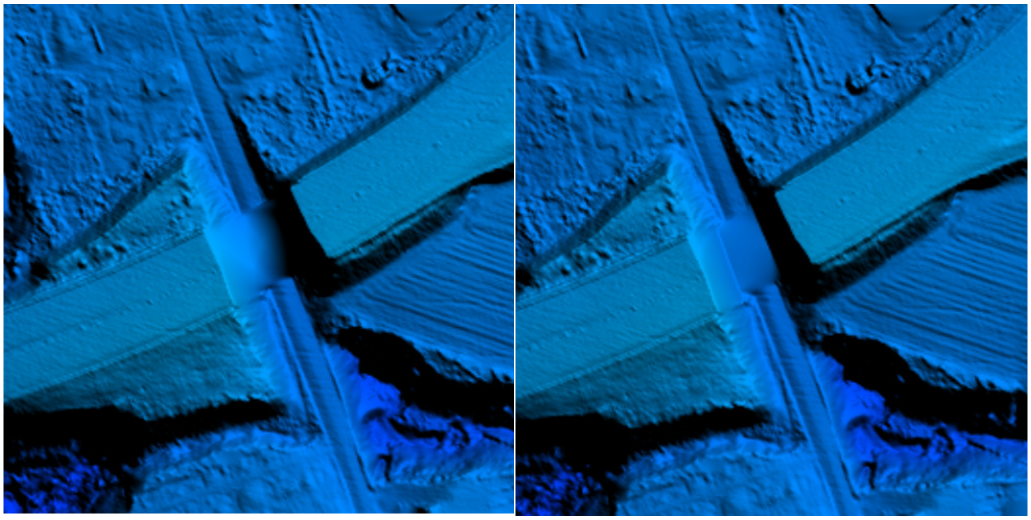

Figure 24- The DEM on the left shows a bridge saddle artifact while the DEM on the right shows the same location after bridge breaklines have been enforced.

DEM VERTICAL ACCURACY RESULTS

The same 250 checkpoints that were used to test the vertical accuracy of the lidar were used to validate the vertical accuracy of the final DEM products as well. Accuracy results may vary between the source lidar and final DEM deliverable. DEMs are created by averaging several lidar points within each pixel which may result in slightly different elevation values at each survey checkpoint when compared to the source LAS, which does not average several lidar points together but may interpolate (linearly) between two or three points to derive an elevation value. The vertical accuracy of the DEM is tested by extracting the elevation of the pixel that contains the x/y coordinates of the checkpoint and comparing these DEM elevations to the surveyed elevations. Dewberry typically uses LP360 software to test the swath lidar vertical accuracy, Terrascan software to test the classified lidar vertical accuracy, and Esri ArcMap to test the DEM vertical accuracy so that three different software programs are used to validate the vertical accuracy for each project.

Table 21 summarizes the tested vertical accuracy results from a comparison of the surveyed checkpoints to the elevation values present within the final DEM dataset.

Land Cover Category	# of Points	NVA – Non-vegetated Vertical Accuracy ($RMSE_z$ x 1.9600) Spec=19.6 cm	VVA – Vegetated Vertical Accuracy (95th Percentile) Spec=29.4 cm
NVA	148	0.102	
VVA	102		0.160

Table 21 – DEM tested NVA and VVA

This DEM dataset was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 10 cm RMSEz Vertical Accuracy Class. Actual NVA accuracy was found to be $RMSE_z$ =5.2 cm, equating to +/- 10.2 cm at 95% confidence level. Actual VVA accuracy was found to be +/- 16 cm at the 95th percentile.

Table 22 lists the 5% outliers that are larger than the VVA 95th percentile.

Point ID	NAD83(2011) UTM Zone 15		NAVD88 (Geoid 12B)	DEM Z (m)	Delta Z	AbsDeltaZ
	Easting X (m)	Northing Y (m)	Survey Z (m)			
VVA-118	354637.339	3580745.028	95.454	95.647	0.193	0.193012
VVA-129	362737.261	3603656.536	141.329	141.503	0.174	0.174
VVA-142	308302.465	3622298.024	100.867	101.099	0.232	0.232
VVA-161	351062.779	3671328.109	123.894	124.158	0.264	0.264
VVA-190	354168.688	3730693.844	100.479	100.640	0.161	0.161

Table 22 – 5% Outliers

Table 23 provides overall descriptive statistics.

100 % of Totals	# of Points	RMSEz (m) NVA Spec=0.1 m	Mean (m)	Median (m)	Skew	Std Dev (m)	Kurtosis	Min (m)	Max (m)
NVA	148	0.052	-0.001	0.003	-0.661	0.052	0.933	-0.190	0.098
VVA	102	N/A	0.037	0.035	0.626	0.076	1.020	-0.142	0.283

Table 23 – Overall Descriptive Statistics

Based on the vertical accuracy testing conducted by Dewberry, the DEM dataset for the Texas Red River FEMA R6 Lidar Project satisfies the project's pre-defined vertical accuracy criteria.

DEM CHECKLIST

The following table represents a portion of the high-level steps in Dewberry's bare earth DEM Production and QA/QC checklist that were performed for this project.

Pass/Fail	Validation Step
Pass	Masspoints (LAS to multipoint) are created from ground points only (class 2 and class 8 if model key points created, but no class 10 ignored ground points or class 9 water points
Pass	Create a terrain for each production block using the final bare earth lidar points and final breaklines.
Pass	Convert terrains to rasters using project specifications for grid type, formatting, and cell size
Pass	Create hillshades for all DEMs
Pass	Manually review bare-earth DEMs in ArcMap with hillshades to check for issues
Pass	DEMs should be hydro-flattened or hydro-enforced as required by project specifications
Pass	DEMs should be seamless across tile boundaries
Pass	Water should be flowing downhill without excessive water artifacts present
Pass	Water features should NOT be floating above surrounding
Pass	Bridges should NOT be present in bare-earth DEMs.

Pass	Any remaining bridge saddles where below bridge breaklines were not used need to be fixed by adding below bridge breaklines and re-processing.
Pass	All qualitative issues present in the DEMs as a result of lidar processing and editing issues must be marked for corrections in the lidar These DEMs will need to be recreated after the lidar has been corrected.
Pass	Calculate DEM Vertical Accuracy including NVA, VVA, and other statistics
Pass	Split the DEMs into tiles according to the project tiling scheme
Pass	Verify all properties of the tiled DEMs, including coordinate reference system information, cell size, cell extents, and that compression has not been applied to the tiled DEMs
Pass	Load all tiled DEMs into Global Mapper to verify complete coverage to the (buffered) project boundary and that no tiles are corrupt.

Table 24-A subset of the high-level steps from Dewberry’s bare earth DEM Production and QA/QC checklist performed for this project.

Appendix A: Complete List of Delivered Tiles

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Appendix B: Quantum Spatial GPS Processing

Appendix B is a separate document located in the Reports folder of the deliverables.

Appendix C: Precision Aerial Reconnaissance GPS Processing

Appendix C is a separate document located in the Reports folder of the deliverables.