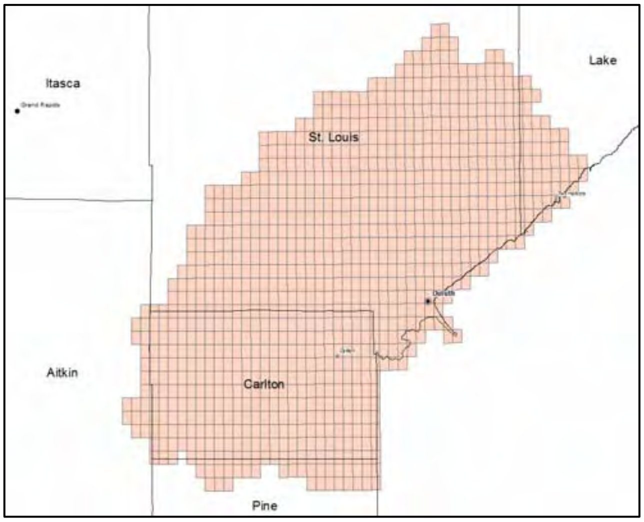
AIRBORNE LiDAR ACQUISITION REPORT



2012 STATE OF MINNESOTA LIDAR PROJECT: WORK ORDER #7 DULUTH FLOOD AREA

MINNESOTA DEPARTMENT OF NATURAL RESOURCES

WOOLPERT PROJECT NUMBER: 72881

PREPARED BY: WOOLPERT, INC.

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June 2013

WOOLPERT
DESIGN | GEOSPATIAL | INFRASTRUCTURE

AIRBORNE LIDAR ACQUISITION REPORT

2012 STATE OF MINNESOTA LIDAR PROJECT

WORK ORDER #7

DULUTH FLOOD AREA

For:

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(MnDNR)
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SECTION 1: OVERVIEW

2012 STATE OF MINNESOTA LIDAR PROJECT: WORK ORDER #7 DULUTH FLOOD AREA

WOOLPERT PROJECT #72881

This report contains a comprehensive outline of the airborne LiDAR data acquisition of Work Order #7 Duluth Flood Area. The Minnesota Elevation mapping project was developed by the Minnesota Digital Elevation Mapping Committee and executed by Minnesota State agencies with the assistance of the federal government and county governments to acquire a highly accurate land surface elevation dataset for the State of Minnesota. High accuracy elevation data are essential to improving water quality, improving disaster preparedness, protecting existing infrastructure, planning flood and drought damage mitigation reports, enhancing natural resource protection, and strengthening decision-making capacity at all levels of government. The geographic area of this work order includes the Minnesota counties of Lake, St Louis, Aitkin, Carlton, and Pine. There are a total of 964 - 1/16 USGS 1:24,000 scale quadrangle tiles covering a land area of approximately 3,078 sq. miles, along with a 100-meter buffer beyond the project tile boundary.

The data was collected using a Leica ALS70 LiDAR sensor and an Optech ALTM Gemini LiDAR sensor. Both sensors collect up to four returns (echo) per pulse, recording attributes such as time stamp and intensity data, for the first three returns. If a fourth return was captured, the system does not record an associated intensity value. The LiDAR was collected at the following sensor specifications for 1.5 NPS:

ALS70 Specifications

Post Spacing (Minimum):	4.92 ft / 1.5 m
AGL (Above Ground Level) average flying height:	7,799 ft / 2,377.1 m
MSL (Mean Sea Level) average flying height:	8,392 ft / 2,557.9m
Average Ground Speed:	150 knots / 172.6 mph
Field of View (full):	40 degrees
Pulse Rate:	115 kHz
Scan Rate:	25 Hz
Side Lap (Minimum):	25%

Optech ALTM Gemini Specifications

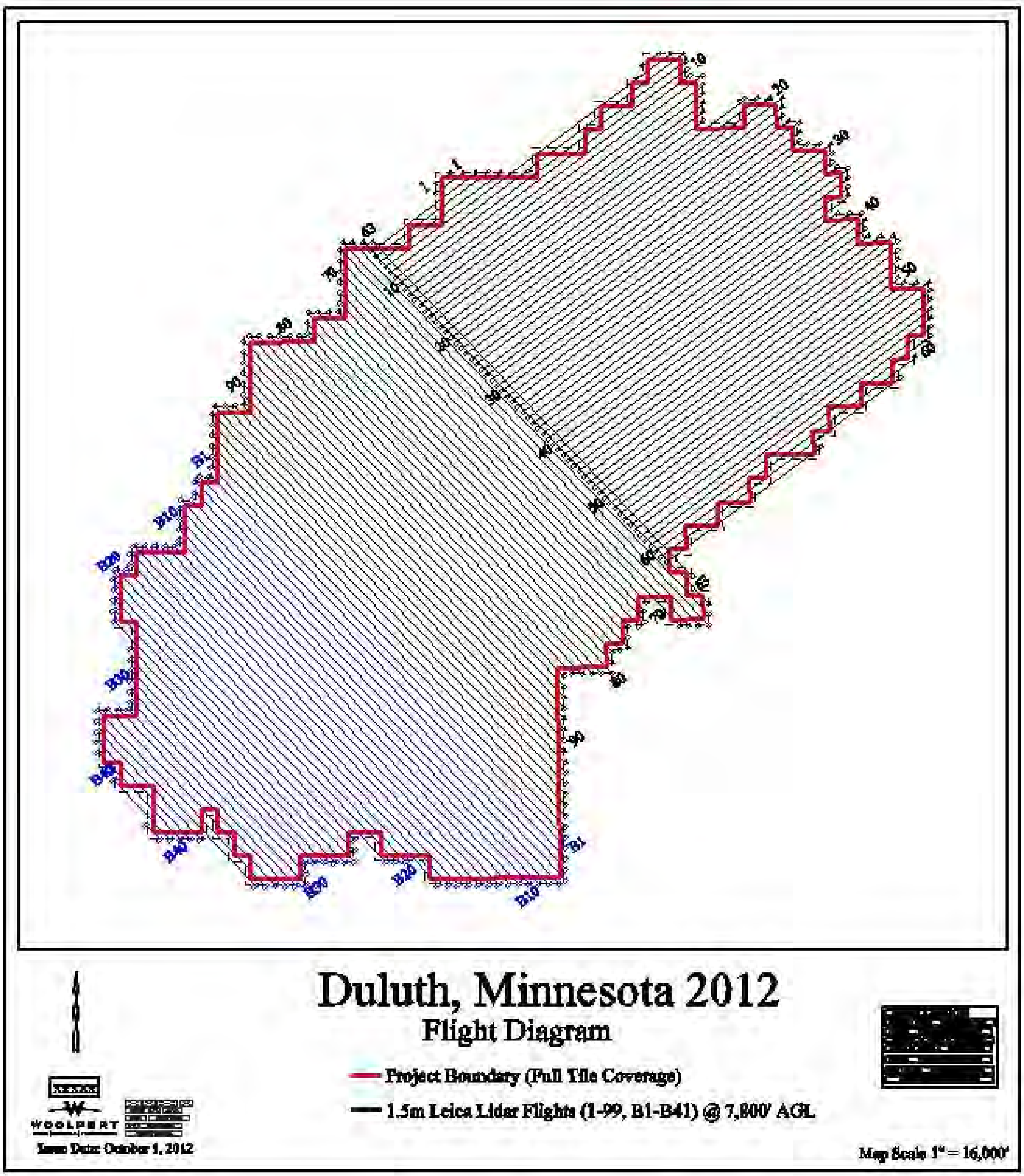
Post Spacing (Minimum):	4.92 ft / 1.5 m
AGL (Above Ground Level) average flying height:	6,800 ft / 2,072.6 m
MSL (Mean Sea Level) average flying height:	7,400 ft / 2255.5 m
Average Ground Speed:	150 knots / 172.6 mph
Field of View (full):	40 degrees
Pulse Rate:	100 kHz
Scan Rate:	29 Hz
Side Lap (Minimum):	25%

The LiDAR was collected and processed to meet a Nominal Post Spacing (NPS) of 1.5 meters. The NPS assessment is made against single swath, first return data located within the geometrically usable center portion (typically ~90%) of each swath.

LiDAR data was processed and projected in UTM 15, North American Datum of 1983 (NAD83) in units of meters. The vertical datum used for the project was referenced to NAVD 1988, meters, Geoid09.

In addition, breaklines defining waterbodies and streams were used to hydrologically flatten the DEM surface. This surface will be inserted into the 1/9 arc-second (3-meter) National Elevation Database.

Figure 1.1 LiDAR Flight Layout



SECTION 2: ACQUISITION

The LiDAR data was acquired with a Leica ALS70 500 kHz MPiA LiDAR sensor, on board a Cessna 404. In addition, data was acquired with an ALTM Gemini, developed by Optech Incorporated of Ontario, Canada. A Dell Precision laptop computer serves as the operator interface using ALTM-NAV™ Flight Management Software.

The ALS LiDAR systems, developed by Leica Geosystems of Heerbrugg, Switzerland, include the simultaneous first, intermediate and last pulse data capture module, the extended altitude range module, and the target signal intensity capture module. The system software is operated on an OC50 Operation Controller and an OC60 Operation Controller aboard the aircraft.

The ALS70 500 kHz Multiple Pulses in Air (MPiA) LiDAR System has the following specifications:

Table 2.1 ALS70 LiDAR System Specifications

Specification	
Operating Altitude	200 – 3,500 meters
Scan Angle	0 to 75° (variable)
Swath Width	0 to 1.5 X altitude (variable)
Scan Frequency	0 – 200 Hz (variable based on scan angle)
Maximum Pulse Rate	500 kHz (Effective)
Range Resolution	Better than 1 cm
Elevation Accuracy	7 - 16 cm single shot (one standard deviation)
Horizontal Accuracy	5 – 38 cm (one standard deviation)
Number of Returns per Pulse	7 (infinite)
Number of Intensities	3 (first, second, third)
Intensity Digitization	8 bit intensity + 8 bit AGC (Automatic Gain Control) level
MPiA (Multiple Pulses in Air)	8 bits @ 1nsec interval @ 50kHz
Laser Beam Divergence	0.22 mrad @ $1/e^2$ (~0.15 mrad @ 1/e)
Laser Classification	Class IV laser product (FDA CFR 21)
Eye Safe Range	400m single shot depending on laser repetition rate
Roll Stabilization	Automatic adaptive, range = 75 degrees minus current FOV
Power Requirements	28 VDC @ 25A
Operating Temperature	0-40°C
Humidity	0-95% non-condensing
Supported GNSS Receivers	Ashtech Z12, Trimble 7400, Novatel Millenium

The Optech Gemini 167 kHz Multiple Pulses in Air (MPiA) LiDAR System has the following specifications:

Table 2.2 ALTM Gemini LiDAR System Specifications

Specification	
Operating Altitude	150 - 4,000 m AGL nominal, 10% reflective target
Scan Angle	0 to 50° (variable)
Swath Width	0 to 1.5 X altitude (variable)
Scan Frequency	0 – 70 Hz (variable based on scan angle)
Maximum Pulse Rate	167 kHz
Range Resolution	Better than 1 cm
Elevation Accuracy	5 –35 cm single shot 1 σ (one standard deviation)
Horizontal Accuracy	1/5,5000 x altitude (m AGL)
Number of Returns per Pulse	4 (first, second, third, last)
Number of Intensities	3 (first, second, third)
Intensity Digitization	12 bit dynamic measurement range
Laser Beam Divergence	Dual divergence: 0.25 mrad (1/e) and 0.8 mrad (1/e), nominal
Laser Classification	Class IV laser product (FDA CFR 21)
Eye Safe Range	400m single shot depending on laser repetition rate
Roll compensation	±5° at full FOV
Power Requirements	28 VDC @ 35A
Data storage	Ruggedized removable SCSI hard disk

Prior to mobilizing to the project site, Woolpert flight crews coordinated with the necessary Air Traffic Control personnel to ensure airspace access.

Woolpert survey crews were onsite, operating a Global Navigation Satellite System (GNSS) Base Station for the airborne GPS support.

The LiDAR data was collected in 11 separate missions, flown as close together as the weather permitted, to ensure consistent ground conditions across the project area.

An initial quality control process was performed immediately on the LiDAR data to review the data coverage, airborne GPS data, and trajectory solution. Any gaps found in the LiDAR data were relayed to the flight crew, and the area was re-flown.

Figure 2.1 LiDAR Flight Layout

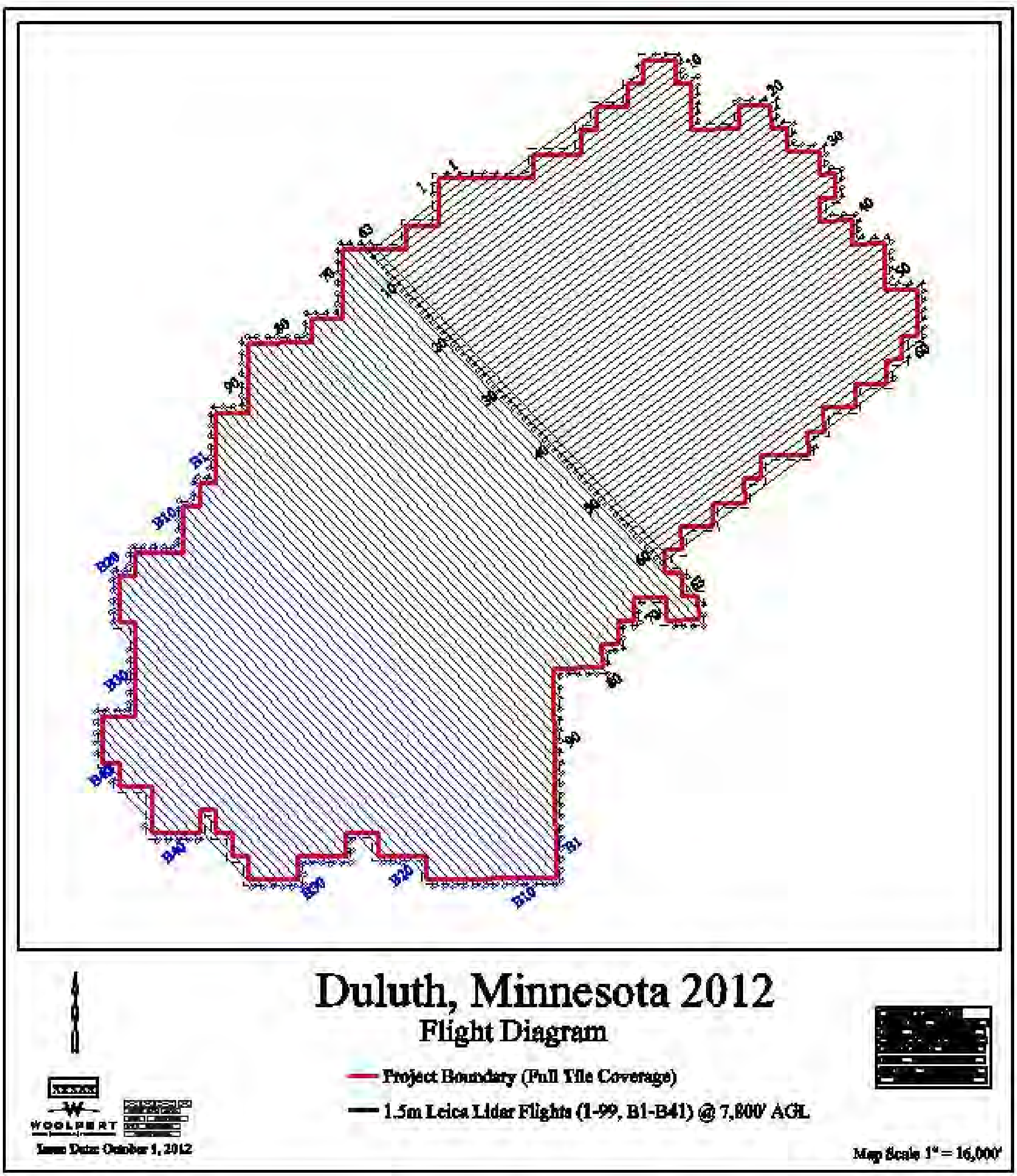


Table 2.3 Airborne LiDAR Acquisition Flight Summary

Airborne LiDAR Acquisition Flight Summary			
Date of Mission – Sensor Number	Lines Flown	Mission Time (UTC) Wheels Up/ Wheels Down	Mission Time (Local = CDT) Wheels Up/ Wheels Down
October 29, 2012 A ALTM_SN56108_N1107Q	1-2, 34-36, 44-46, 69-73 (Optech Flights)	13:39 – 19:02	9:39AM -2:02PM
October 29, 2012 B ALTM_SN56108_N1107Q	54-68 (Optech Flights)	19:52 – 01:22	2:52PM – 8:22PM
October 30, 2012 A ALTM_SN56108_N1107Q	38-44, 46-53 (Optech Flights)	16:11 - 21:56	11:11AM - 4:56PM
October 30, 2012 B ALTM_SN56108_N1107Q	23-35, 37 (Optech Flights)	23:50 – 05:39	06:50PM – 12:39AM
October 30, 2012 ALS70_SN7177_N475RC	20-41 (Leica Flights)	18:47 – 23:17	01:47PM – 06:17PM
October 31, 2012 B ALTM_SN56108_N1107Q	1-22 (Optech Flights)	16:43 – 22:44	11:43AM – 05:44PM
October 31, 2012 ALS70_SN7177_N475RC	1-19 (Leica Flights)	15:22 – 22:03	10:22AM – 05:03PM
November 2, 2012 A ALTM_SN56108_N1107Q	8 (Optech Flights)	15:56 – 17:36	10:56AM – 12:36PM
November 2, 2012 B ALTM_SN56108_N1107Q	1-2, 35-36, 44-45, 74-82 (Optech Flights)	18:12 – 00:15	1:12PM – 07:15PM
November 2, 2012 ALS70_SN7177_N475RC	79-98 (Leica Flights)	14:34 – 22:03	9:34AM - 05:56PM
November 8, 2012 ALS70_SN7177_N475RC	69-78 (Leica Flights)	14:04 – 17:33	9:04AM – 11:33AM

SECTION 3: LIDAR DATA PROCESSING

APPLICATIONS AND WORK FLOW OVERVIEW

1. Resolved kinematic corrections for three subsystems: inertial measurement unit (IMU), sensor orientation information and airborne GPS data. Developed a blending post-processed aircraft position with attitude data using Kalman filtering technology or the smoothed best estimate trajectory (SBET).
   Software: POSPac Software v. 5.3, IPAS Pro v.1.3.

2. Calculated laser point position by associating the SBET position to each laser point return time, scan angle, intensity, etc. Created raw laser point cloud data for the entire survey in .LAS format. Automated line-to-line calibrations were then performed for system attitude parameters (pitch, roll, heading), mirror flex (scale) and GPS/IMU drift.
   Software: ALS Post Processing Software v.2.75, Dashmap v5.1061 Proprietary Software, TerraMatch v. 12.05.

3. Imported processed .LAS point cloud data into project tiles. Resulting data were classified as ground and non-ground points with additional filters created to meet the project classification specifications. Statistical absolute accuracy was assessed via direct comparisons of ground classified points to ground RTK survey data. Based on the statistical analysis, the LiDAR data was then adjusted to reduce the vertical bias when compared to the survey ground control.
   Software: TerraScan v.12.05

4. The .LAS files were evaluated through a series of manual QA/QC steps to eliminate remaining artifacts and small undulations from the ground class.
   Software: TerraScan v.12.05

5. All water bodies greater than two acres and all rivers with a nominal 100 foot width or larger were hydro-flattened using proprietary software.
   Software: TerraScan v.12.05, TerraModeler v.12.05, ArcMAP 10.1, LP360, Proprietary Software

GLOBAL NAVIGATION SATELLITE SYSTEM (GNSS)-INERTIAL MEASUREMENT UNIT (IMU) TRAJECTORY PROCESSING

EQUIPMENT

Flight navigation during the LiDAR data acquisition mission is performed using IGI CCNS (Computer Controlled Navigation System). The pilots are skilled at maintaining their planned trajectory, while holding the aircraft steady and level. If atmospheric conditions are such that the trajectory, ground speed, roll, pitch and/or heading cannot be properly maintained, the mission is aborted until suitable conditions occur.

The aircraft are all configured with a NovAtel Millennium 12-channel, L1/L2 dual frequency Global Navigation Satellite System (GNSS) receivers collecting at 2 Hz.

All Woolpert aerial sensors are equipped with a Litton LN200 series Inertial Measurement Unit (IMU) operating at 200 Hz.

A base-station unit was mobilized for the imagery acquisition mission, and was operated by a member of the Woolpert survey crew and/or flight crew. Each base-station setup consisted of one (1) Trimble 5000 series dual frequency receiver, one (1) Trimble Zephyr Geodetic L1/L2 dual frequency antenna, one (1) 2-meter fixed-height tripod, and essential battery power and cabling. Ground planes were used on the base-station antennas. Data was collected at 1 or 2 Hz.

Woolpert survey crews were onsite, operating a Global Navigation Satellite System (GNSS) Base Station during the LiDAR acquisition missions is listed below:

Table 3.1: GNSS Base Station

Mission (Julian Day – Sensor)	Station	Latitude	Longitude	Ellipsoid Height (L1 Phase Center)
DDDYY_Sensor	Name	(DMS)	(DMS)	(Meters)
Day30312_OP108_A	Duluth	46°50'23.43878"	92°11'39.08125"	404.501
Day30312_OP108_B	Duluth	46°50'23.43878"	92°11'39.08125"	404.501
Day30412_OP108_A	Duluth	46°50'23.43878"	92°11'39.08125"	404.501
Day30412_OP108_B	Duluth	46°50'23.43878"	92°11'39.08125"	404.501
Day30412_SH7177	MNPL CORS	46°20'22.33850"	93°15'43.48453"	355.141
Day30512_OP108	Duluth	46°50'23.43878"	92°11'39.08125"	404.501
Day30512_SH7177	NGS PID DN9484	46°42'14.26501"	92°30'15.59644"	360.47
Day30712_OP108_A	Duluth	46°50'23.43878"	92°11'39.08125"	404.501
Day30712_OP108_B	Duluth	46°50'23.43878"	92°11'39.08125"	404.501
Day30712_SH7177	Duluth	46°50'23.43878"	92°11'39.08125"	404.501
Day31312_SH7177	Duluth	46°50'23.43878"	92°11'39.08125"	404.501

DATA PROCESSING

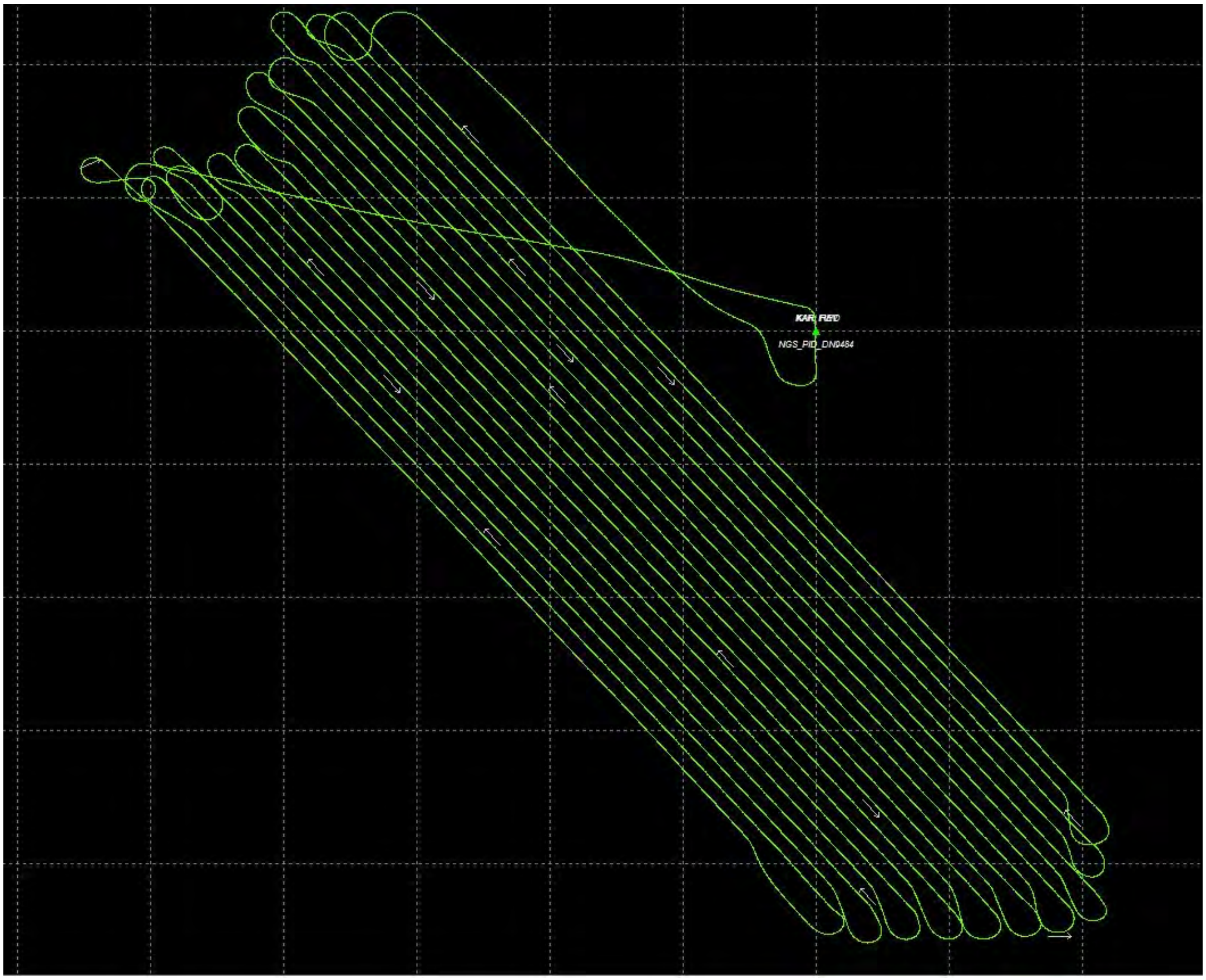
All airborne GNSS and IMU data was post-processed and quality controlled using Applanix 5.3 MMS software. GNSS data was processed at a 1 and 2 Hz data capture rate and the IMU data was processed at 200 Hz.

TRAJECTORY QUALITY

The GNSS Trajectory, along with high quality IMU data are key factors in determining the overall positional accuracy of the final sensor data. See **Figure 3.1** for the flight trajectory.

Flight Trajectory

Figure 3.1: Representative Graph from Day30512: N475RC



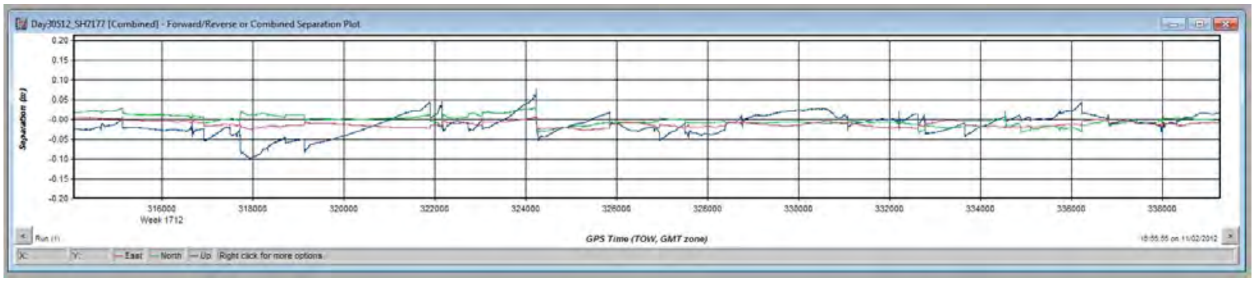
Within the trajectory processing, there are many factors that affect the overall quality, but the most indicative are the Combined Separation, the Estimated Positional Accuracy, and the Positional Dilution of Precision (PDOP).

Combined Separation

The Combined Separation is a measure of the difference between the forward run and the backward run solution of the trajectory. The Kalman filter is processed in both directions to remove the combined directional anomalies. In general, when these two solutions match closely, an optimally accurate reliable solution is achieved.

Woolpert's goal is to maintain a Combined Separation Difference of less than ten (10) centimeters. In most cases we achieve results below this threshold. See **Figure 3.2** for the combined separation graph.

Figure 3.2: Representative Graph from Day30512: N475RC of Combined Separation

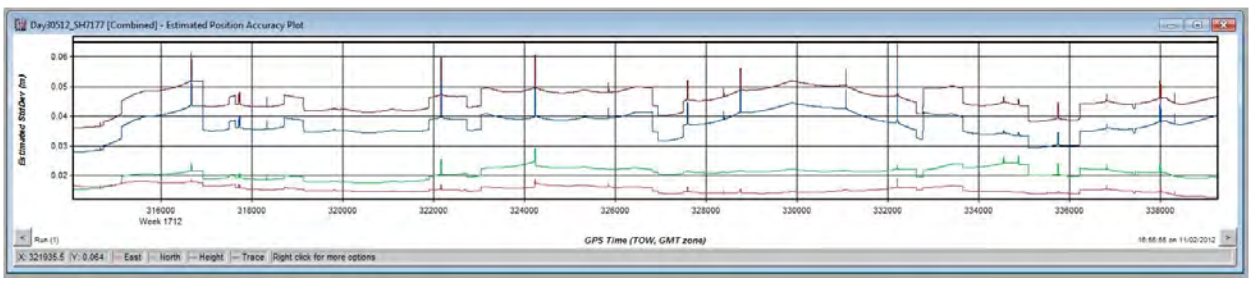


Estimated Positional Accuracy

The Estimated Positional Accuracy plots the standard deviations of the east, north, and vertical directions along a time scale of the trajectory. It illustrates loss of satellite lock issues, as well as issues arising from long baselines, noise, and/or other atmospheric interference.

Woolpert's goal is to maintain an Estimated Positional Accuracy of less than ten (10) centimeters, often achieving results well below this threshold.

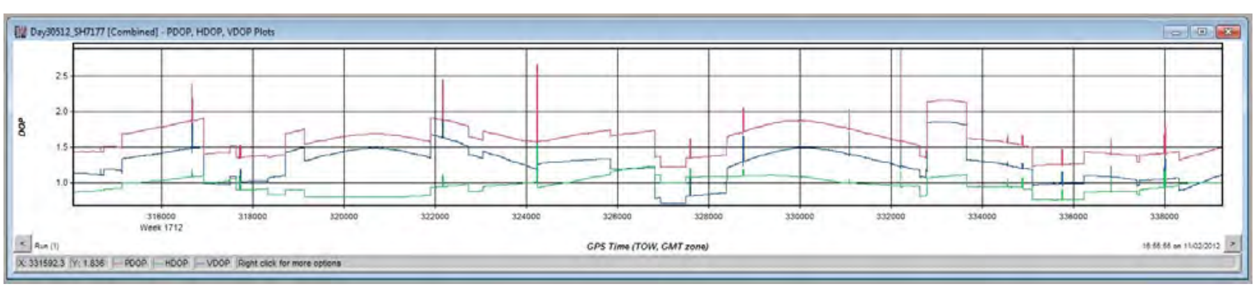
Figure 3.3: Representative Graph from Day30512: N475RC of Positional Accuracy



Positional DILUTION OF PRECISION (PDOP)

The PDOP measures the precision of the GPS solution in regards to the geometry of the satellites acquired and used for the solution. Woolpert's goal is to maintain an average PDOP value below 3.0. Brief periods of PDOP over 3.0 are acceptable due to the calibration and control process if other metrics are within specification. See **Figure 3.4** for plots of PDOP of each mission and sensor.

Figure 3.4: Representative Graph from Day30512: N475RC of PDOP



LIDAR DATA PROCESSING

When the sensor calibration, data acquisition, and GPS processing phases were complete, the formal data reduction processes by Woolpert LiDAR specialists included:

- Processed individual flight lines to derive a raw "Point Cloud" LAS file. Matched overlapping flight lines, generated statistics for evaluation comparisons, and made the necessary adjustments to remove any residual systematic error.

- Calibrated LAS files were imported into the task order tiles and initially filtered to create a ground and non-ground class. Then additional classes were filtered as necessary to meet client specified classes.

- Once all of the task order data was imported and classified, cross flights and survey ground control data was imported and calculated for an accuracy assessment. As a QA/QC measure, Woolpert has developed a routine to generate accuracy statistical reports by comparison among LiDAR points, ground control, and TINs. The LiDAR is adjusted accordingly to reduce any vertical bias to meet or exceed the vertical accuracy requirements.

- The LiDAR tiles were reviewed using a series of proprietary QA/QC procedures to ensure it fulfills the task order requirements. A portion of this requires a manual step to ensure anomalies have been removed from the ground class.

- The bare earth DEM surface was hydrologically flattened for waterbody features that were greater than 2 acres and rivers and streams of 30.5 meters (100 feet) and greater nominal width.

- The LiDAR LAS files for this task order have been classified into the Default (Class 1), Ground (Class 2), Low Vegetation (Class 3), Medium Vegetation (Class 4), High Vegetation (Class 5) Buildings (Class 6), Noise (Class 7), Model Keypoints (Class 8), Water (Class 9), Ignored Ground (Class 10), bridges (Class 14), and Overlap (Class 17) classifications.

- FGDC Compliant metadata was developed for the task order in .xml format for the final data products.

- The horizontal datum used for the task order was referenced to UTM 15N and North American Datum of 1983. Coordinate positions were specified in units of meters. The vertical datum used for the task order was referenced to NAVD 1988, meters, Geoid09.

SECTION 4: HYDROLOGIC FLATTENING AND FINAL QUALITY CONTROL

HYDROLOGIC FLATTENING OF LIDAR DEM DATA

This task required the compilation of breaklines defining water bodies and rivers. The breaklines were used to perform the hydrologic flattening of water bodies, and gradient hydrologic flattening of double line rivers. Lakes, reservoirs and ponds, at a minimum size of 2-acres or greater, were compiled as closed polygons. The closed water bodies were collected at a constant elevation. Rivers and streams, at a nominal minimum width of 30.5 meters (100 feet), were compiled in the direction of flow with both sides of the stream maintaining an equal gradient elevation.

LIDAR DATA REVIEW AND PROCESSING

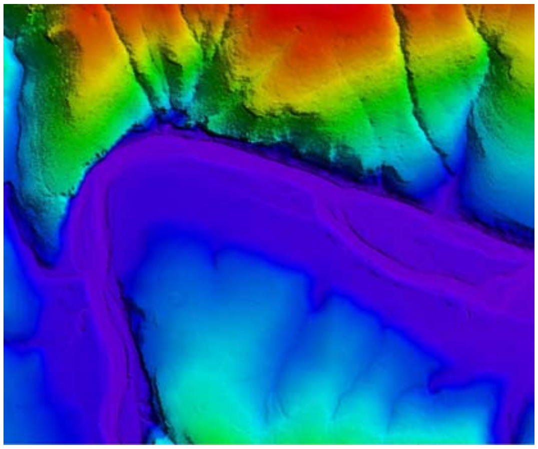
Woolpert utilized the following steps to hydrologically flatten the water bodies and for gradient hydrologic flattening of the double line streams within the existing LiDAR data.

1. Woolpert used a combination of Intensity data and digital elevation models from the 2012 lidar collection as well imagery from open source imagery to manually draw the hydrologic features in a 2D environment

2. Woolpert utilizes an integrated software approach to combine the LiDAR data and 2D breaklines. This process “drapes” the 2D breaklines onto the 3D LiDAR surface model to assign an elevation. A monotonic process is performed to ensure the streams are consistently flowing in a gradient manner. A secondary step within the program verifies an equally matching elevation of both stream edges. The breaklines that characterize the closed water bodies are draped onto the 3D LiDAR surface and assigned a constant elevation at or just below ground elevation.

3. The lakes, reservoirs and ponds, at a minimum size of 2-acres or greater, were compiled as closed polygons. **Figure 4.1** illustrates a good example of 2-acre lakes and 30.5 meters (100-feet) nominal streams identified and defined with hydrologic breaklines. The breaklines defining rivers and streams, at a nominal minimum width of 30.5 meters (100-feet), were draped with both sides of the stream maintaining an equal gradient elevation.

Figure 4.1



4. All ground points were reclassified from inside the hydrologic feature polygons to water, class nine (9).

5. All ground points were reclassified from within a 1.5 meter (5-foot) buffer along the hydrologic feature breaklines to buffered ground, class ten (10).

6. The LiDAR ground points and hydrologic feature breaklines were used to generate a new digital elevation model (DEM).

Figure 4.2

Figure 4.3

Figure 4.2 reflects a DEM generated from original LiDAR bare earth point data prior to the hydrologic flattening process. Note the "tinning" across the lake surface.

Figure 4.3 reflects a DEM generated from LiDAR with breaklines compiled to define the hydrologic features. This figure illustrates the results of adding the breaklines to hydrologically flatten the DEM data. Note the smooth appearance of the lake surface in the DEM.

Terrascan was used to add the hydrologic breakline vertices and export the lattice models. The hydrologically flattened DEM data was provided to MNDNR in ArcGRID 32-bit FLOAT format at a 1-meter cell size. The final LiDAR data was delivered in a client provided projection tiling format, based on 1:24,000 scale quadrangle tiles.

The hydrologic breaklines compiled as part of the flattening process were provided to the MNDNR as an ESRI Polygon Z shapefile in file geodatabase format.

DATA QA/QC

Initial QA/QC for this task order was performed in Global Mapper v14, by reviewing the grids and hydrologic breakline features.

Edits and corrections were addressed individually by tile. If a water body breakline needed to be adjusted to improve the flattening of the ArcGRID DEM, the area was cross referenced by tile number, corrected accordingly, a new ArcGRID DEM was regenerated and then reviewed in Global Mapper.

SECTION 5: FINAL ACCURACY ASSESSMENT

FINAL VERTICAL ACCURACY ASSESSMENT

The vertical accuracy statistics were calculated by comparison of the LiDAR bare earth points to the ground surveyed QA/QC points.

Table 5.1: Overall Vertical Accuracy Statistics

Average error	-0.007	meters
Minimum error	-0.094	meters
Maximum error	0.064	meters
Average magnitude	0.029	meters
Root mean square	0.036	meters
Standard deviation	0.037	meters

Table 5.2: QA/QC Analysis UTM 15N, NAD83

Point ID	Easting (UTM meters)	Northing (UTM meters)	Elevation (meters)	Laser Elevation (meters)	Dz (meters)
1002	555322.1	5142357	395.014	394.92	-0.094
1005	548134	5225874	417.77	417.81	0.04
1013	588236.9	5230752	469.904	469.89	-0.014
1033	529366.3	5168429	394.246	394.26	0.014
1043	496280	5167504	396.711	396.68	-0.031
1044	599534.4	5208712	228.444	228.41	-0.034
1046	554678.2	5167359	190.506	190.53	0.024
1054	574279.1	5247180	484.856	484.92	0.064
1059	551765.2	5190082	428.999	428.97	-0.029
1062	575038.8	5206400	434.569	434.6	0.031
1208	535368.1	5135762	352.176	352.14	-0.036
1211	531276.2	5222300	397.287	397.29	0.003
1212	550510	5202241	409.667	409.64	-0.027
2006	505748.6	5196887	384.33	384.33	0
6003	563036.3	5190559	429.153	429.14	-0.013
6006	582137.3	5192569	191.401	191.4	-0.001
6010	572217.1	5175765	184.22	184.2	-0.02
6012	569037.1	5181765	186.196	186.14	-0.056

Point ID	Easting (UTM meters)	Northing (UTM meters)	Elevation (meters)	Laser Elevation (meters)	Dz (meters)
6020	558267.2	5184077	416.649	416.68	0.031
6021	558592.5	5177105	381.207	381.22	0.013

VERTICAL ACCURACY CONCLUSIONS

- **Data Accuracy**: LAS Swath Fundamental Vertical Accuracy (FVA) Tested 0.071 meters fundamental vertical accuracy at a 95 percent confidence level, derived according to NSSDA, in open terrain using (RMSEz) x 1.96000 Tested against the TIN using independent check points.

Approved By:			
Title	Name	Signature	Date
Associate Member LiDAR Specialist Certified Photogrammetrist #1281	Qian Xiao		June 5, 2013

SECTION 6: FINAL DELIVERABLES

FINAL DELIVERABLES

The final deliverables are listed below. The final LiDAR data was delivered in a UTM/Meter projection tiling format, based on 1:24,000 scale quadrangle tiles. The tiles were provided with 50 meters of overlap between adjacent tiles and along the project border.

- LAS v1.2 classified point cloud.
- LAS v1.2 raw unclassified point cloud flight line strips no greater than 2GB, per area (Long swaths greater than 2GB will be split into segments).
- Breaklines compiled as part of the hydrologic flattening process were provided as ESRI PolygonZ. These were delivered as part of a file geodatabase.
- ESRI multipoint feature class representing bare earth. These were delivered as part of a file geodatabase.
- 1 meter ArcGrid DEM. These were delivered as part of a file geodatabase.
- FGDC compliant metadata by file in XML format.

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