USGS
LiDAR Campaign
Final Report
For
Puget Sound
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EXECUTIVE SUMMARY

In the spring of 2006, Sanborn was contracted by the USGS to execute a LiDAR (Light Detection and Ranging) survey campaign in the state of Washington. LiDAR data in the form of 3-dimensional positions of a dense set of mass points was collected for the 1735 square miles of western Whatcom and Skagit Counties. This data was used in the development of the bare-earth-classified elevation point data sets.

The Leica ALS-50 (Airborne Laser Terrain Mapping) and the Optech 2050 LiDAR systems were used to collect data for the whole survey campaign. The LiDAR system is calibrated by conducting flight passes over a known ground surface before and after each LiDAR mission. During final data processing, the calibration parameters are inserted into post-processing software.

Six airborne GPS (Global Positioning System) base stations were used in this project. A new point was set at the Skagit Regional Airport (501). The other base stations were set up at National Geodetic Survey (NGS) markers. NGS Monument 701 – PID: TR2747, located at the Skagit Regional Bay View Airport and 702 – PID: TQ0548, located northeast of Marblemount. The other existing NGS monuments used in the network point 901 – PID: TR0036, located near the town of Bellingham, point 902 – PID: TR0222, located northwest of Mount Vernon, and lastly point 903 – PID: TR0023, located in the town of Lyman were tied to the other three points to create a GPS survey network. The coordinates of these stations were checked against each other with the three dimensional GPS baseline created at the airborne support set up and determined to be within project specifications.

The acquired LiDAR data was processed to obtain first and last return point data. The last return data was further filtered to yield a LiDAR surface representing the bare earth.

The contents of this report summarize the methods used to establish the base station coordinate check, perform the LiDAR data collection and post-processing as well as the results of these methods.

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1 INTRODUCTION

This report contains the technical write-up of the USGS LiDAR campaign, including system calibration techniques, the establishment of base stations by a differential GPS network survey, and the collection and post-processing of the LiDAR data.

1.1 Contact Information

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1.2 Purpose of the LiDAR Acquisition

This LiDAR operation was designed to provide a highly detailed ground surface dataset to be used for the development of topographic, contour mapping and hydraulic modeling

1.3 Project Location

Puget Sound, Washington. See Figure 1.

1.4 Project Scope, Specifications and Time Line

The spring of 2006 LiDAR Flight Acquisition required the collection of 1735 square miles collected at a nominal point spacing of 1.4 meters and based on the Sanborn FEMA compliant LiDAR product specification. See Table 1.

Table 1: Project Specifications and Deliverable Coordinate and Datum Systems

Area (sq. mi)	1735	**Product type**	Fema(F)	**Projection**	Washington State Plane
Vertical Accuracy (CM)	Bare Earth 18.5 (F)	**Check Points required**	Yes	**Horizontal Datum Vertical Datum**	NAD 83 NAVD 88
Horizontal accuracy (M)	1meter (F)	**Number Collected**	45	**Units**	US Survey Ft

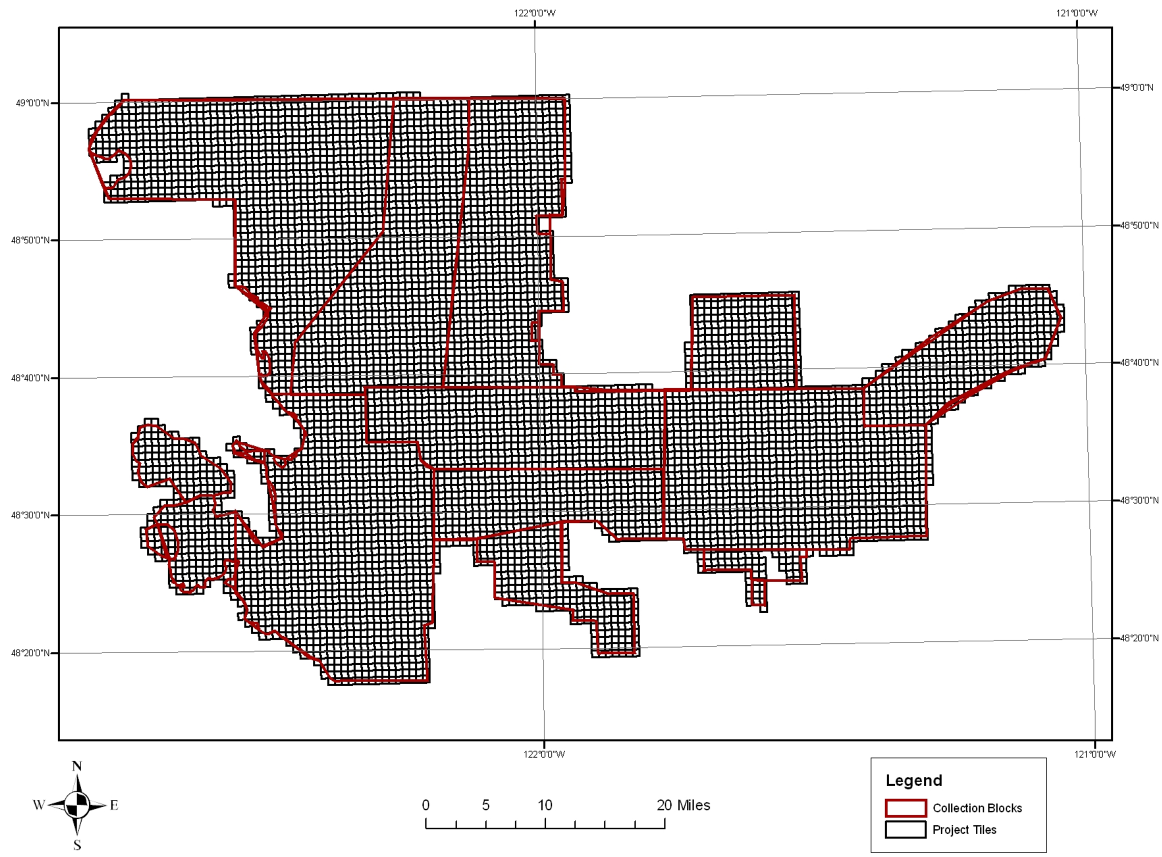

Figure 1: Area of Collection

2 OVERALL LiDAR SYSTEM CALIBRATION

2.1 Introduction

LiDAR calibrations are performed to determine and therefore eliminate systematic biases that occur within the hardware of the Leica ALS-50 and Optech 2050 systems. Once the biases are determined they can be modeled out. The systematic biases are corrected for include scale, roll, and pitch.

The following procedures are intended to prevent operational errors in the field and office work, and are designed to detect inconsistencies. The emphasis is not only on the quality control (QC) aspects, but also on the documentation, i.e., on the quality assurance (QA).

2.2 Calibration Procedures

Sanborn performs two types of calibrations on its LiDAR system. The first is a building calibration, and it is done any time the LiDAR system has been moved from one plane to another. New calibration parameters are computed and compared with previous calibration runs. If there is any change, the new values are updated internally or during the LiDAR post-processing. These values are applied to all data collected with this plane/ALS-50 or ALTM Optech 2050 systems configuration.

Once final processing calibration parameters are established from the building data, a precisely-surveyed surface is observed with the LiDAR system to check for stability in the system. This is done several times during each mission. An average of the systematic biases are applied on a per mission basis.

2.3 Building Calibration

Whenever the ALS-50 and Optech 2050 systems are moved to a new aircraft, a building calibration is performed. The rooftop of a large, flat, rectangular building is surveyed on the ground using conventional survey methods, and used as the LiDAR calibration target. The aircraft flies several specified passes over the building with the ALS-50 and Optech 2050 systems set first in scan mode, then in profile mode, and finally in both scan and profile modes with the scan angle set to zero degrees.

Figure 2 shows a pass over the center of the building. The purpose of this pass is to identify a systematic bias in the scale of the system.

Figure 3 demonstrates a pass along a distinct edge of the building to verify the roll compensation performed by the Inertial Navigation System, INS.

Additionally, a pass is made in profile mode across the middle of the building to compensate for any bias in pitch.

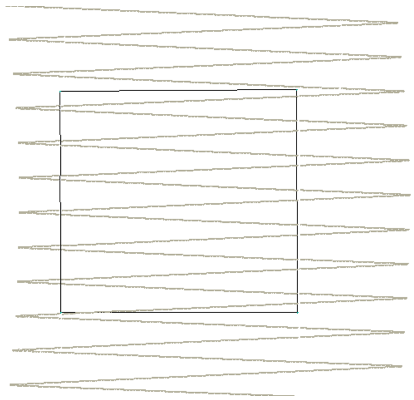

Figure 2: Calibration Pass 1

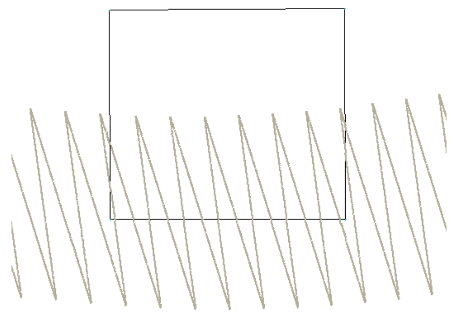

Figure 3: Calibration Pass 2

2.4 Runway Calibration, System Performance Validation

An active asphalt runway was precisely-surveyed at the Skagit Regional Airport using kinematic GPS survey techniques (accuracy: ±3cm at 1σ, along each coordinate axis) to establish an accurate digital terrain model of the runway surface. The LiDAR system is flown at right angles over the runway several times and residuals are generated from the processed data. Figure 4 shows a typical pass over the runway surface.

Approximately 25,000 LiDAR points are observed with each pass. These points are "draped" over the runway surface's Triangular Irregular Network, TIN, to compute vertical residuals for every data point. The residuals are analyzed with respect to the location along the runway to identify the level of noise and system biases.

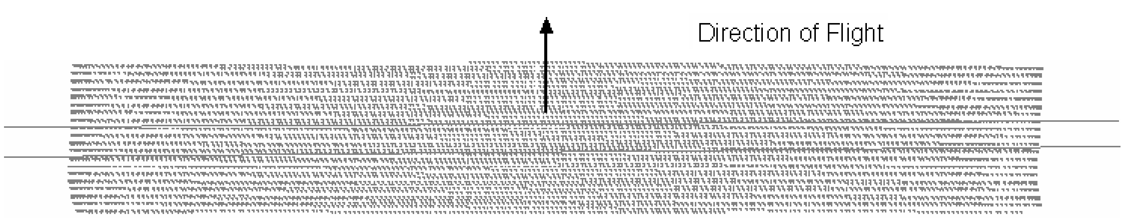

Figure 4: Runway Calibration

3 RUNWAY CALIBRATION, SYSTEM PERFORMANCE VALIDATION

3.1 Overall Calibration Results

The LiDAR data captured over the building is used to determine whether there have been any changes to the alignment of the Inertial Measurement Unit, IMU, with respect to the laser system. The parameters are designed to eliminate systematic biases within certain system parameters.

The runway over-flights are intended to be a quality check on the calibration and to identify any system irregularities and the overall noise. IMU misalignments and internal system calibration parameters are verified by comparing the collected LiDAR points with the runway surface.

Figure 5 shows the typical results of a runway over-flight analysis. The X-axis represents the position along the runway. The overall statistics from this analysis provides evidence of the overall random noise in the data (typically, 7 cm standard deviation – an unbiased estimator, and 8 cm RMS which includes any biases) and indicates that the system is performing within specifications. As described in later sections of this report, this analysis will identify any peculiarities within the data along with mirror-angle scale errors (identified as a “smile” or “frown” in the data band) or roll biases.

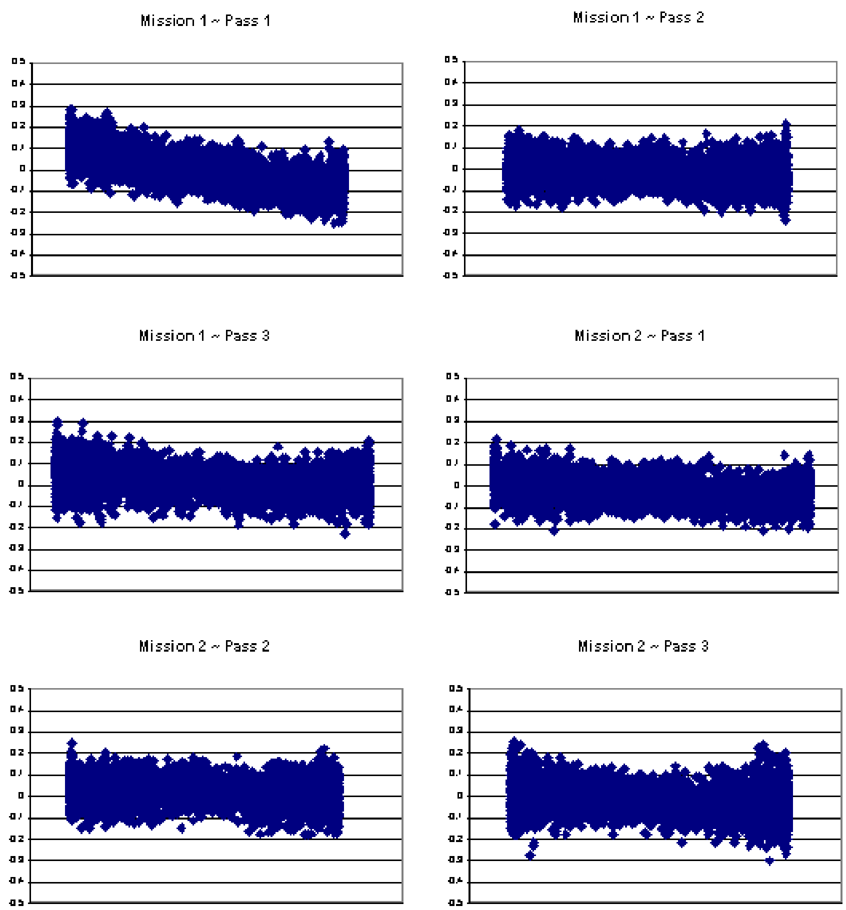

Figure 5: Typical Runway Calibration Results

4 ACQUISITION AND PROCESSING PROCEDURES

4.1 Introduction

This section addresses LiDAR system, flight reporting and data acquisition methodology used during the collection of the Puget Sound campaign. Although Sanborn conducts all LiDAR with the same rigorous and strict procedures and processes, all LiDAR collections are unique.

4.2 Field Work Procedures

A minimum of two GPS base stations were set up, with one receiver located at the airport, and the secondary GPS receiver placed at a survey control point within the project area or within the required baseline specifications of the project. The base station distances are where set for 20 km baseline and did not exceed 40 kilometers in all cases.

Pre-flight checks such as cleaning the sensor head glass are performed. A five minute INS initialization is conducted on the ground, with the engines running, prior to flight, to establish fine-alignment of the INS. GPS ambiguities are resolved by flying within forty kilometers of the base stations.

The flight missions were typically four or five hours in duration including runway calibration flights flown at the beginning and the end of each mission. During the data collection, the operator recorded information on log sheets which includes weather conditions, LiDAR operation parameters, and flight line statistics. Near the end of the mission GPS ambiguities are again resolved by flying within ten kilometers of the base stations, to aid in post-processing.

Table 2 shows the planned LiDAR acquisition parameters for both sensors with a flying height of 1,500 and 1200 meters above ground level (AGL) on a mission to mission basis, respectively. Table 3 shows the flight missions statistics of dates, times, laser settings, and PDOP values.

Table 2: LiDAR Acquisition Parameters

Leica sensor Collection (Low Relief Collection)

Average Altitude	1,500 Meters AGL
Airspeed	~120 Knots
Scan Frequency	36 Hertz
Scan Width Half Angle	20 Degrees
Pulse Rate	60000 Hertz
Overlap	30%

Leica Sensor (High Relief Collection)

Average Altitude	1,500 Meters AGL
Airspeed	~120 Knots
Scan Frequency	36 Hertz
Scan Width Half Angle	36 Degrees
Pulse Rate	60000 Hertz
Overlap	44-60%

Optech 2050 (High and Low Relief Collection)

Average Altitude	1,200 Meters AGL
Airspeed	~120 Knots
Scan Frequency	30 Hertz
Scan Width Half Angle	40 Degrees
Pulse Rate	50000 Hertz
Overlap	30-50%

Preliminary data processing was performed in the field immediately following the missions for quality control of GPS data and to ensure sufficient overlap between flight lines. However thorough our field processing may have been, the final data processing completed in the Colorado Springs office yielded problems. There were areas of data voids between flight lines and several tiles in the southeastern area of the project where no data was collected. Due to the dense tree canopy and vegetation in the area, there were also areas of the project that appeared to have data voids. However, this is not the case. In these areas, the laser was unable to reach the ground and therefore, the data lacks bare earth classification.

Table 3: Collection Dates, Times, Average Per Flight Collection Parameters and PDOP

Mission	Date	Start Time	End Time	Altitude (m)	Airspeed (Knots)	Scan Angle	Scan Rate	Pulse Rate	PDOP
123a	May 3	22:44	01:55	1500	120	40˚	36	60000	1.2
124a	May 4	16:58	19:40	1500	120	40˚	36	60000	0.9
124b	May 4	23:06	2:03	1500	120	40˚	36	60000	1.2
125a	May 5	16:40	19:09	1500	120	40˚	36	60000	1.0
125b	May 5	00:18	02:08	1500	120	40˚	36	60000	1.2
128a	May 8	19:30	21:36	1500	120	40˚	36	60000	1.8
129a	May 9	14:15	19:38	1500	120	40˚	36	60000	1.7
129b	May 9	15:31	18:42	1500	120	40˚	36	60000	1.0
129c	May 9	22:28	01:39	1500	120	40˚	36	60000	1.3
130a	May 10	16:01	20:00	1500	120	40˚	36	60000	1.7
130b	May 10	16:10	17:45	1500	120	40˚	36	60000	1.5
135a	May 15	18:51	22:56	1500	120	40˚	36	60000	1.6
136a	May 16	16:00	19:40	1500	120	40˚	36	60000	1.4
136b	May 16	21:47	01:15	1500	120	40˚	36	60000	1.5
137a	May 17	15:33	19:30	1500	120	40˚	36	60000	1.6
138a	May 18	18:36	22:08	1500	120	40˚	36	60000	1.87
138b	May 18	00:19	03:05	1500	120	40˚	36	60000	1.5
139a	May 19	16:00	19:04	1500	120	40˚	36	60000	1.4
141a	May 21	16:15	20:10	1500	120	40˚	36	60000	1.6
172a	June 21	04:32	09:35	1500	120	40˚	36	60000	1.1
173a	June 22	02:00	07:43	1500	120	40˚	36	60000	1.2
175a	June 24	0:15	3:37	1500	120	40˚	36	60000	1.2
176a	June 25	19:00	22:05	1500	120	40˚	36	60000	1.1
239a	Aug 27	23:00	1:35	1500	120	40˚	36	60000	1.8
239b	Aug 27	3:40	6:34	1500	120	40˚	36	60000	1.8
240a	Aug 28	22:17	1:48	1500	120	40˚	36	60000	1.9
240b	Aug 28	2:54	5:40	1500	120	40˚	36	60000	1.9
243a	Aug 31	17:57	21:35	1500	120	40˚	36	60000	1.7
243b	Aug 31	23:48	08:17	1500	120	40˚	36	60000	1.8
244a	Sept 1	19:33	20:40	1500	120	40˚	36	60000	1.6
244b	Sept 1	21:58	0:20	1500	120	40˚	36	60000	1.8
245a	Sept 2	17:12	20:53	1500	120	40˚	36	60000	1.6
245b	Sept 2	1:04	3:52	1500	120	40˚	36	60000	1.9
246a	Sept 3	19:35	23:19	1500	120	40˚	36	60000	1.9
246b	Sept 3	0:51	3:09	1500	120	40˚	36	60000	1.8

4.3 Final LiDAR Processing

Final post-processing of LiDAR data involves several steps. The airborne GPS data was post-processed using Waypoint's GravNAV^{TM} software (version 7.5). A fixed-bias carrier phase solution was computed in both the forward and reverse chronological directions. The data was processed for both base stations and combined. In the event that the solution worsened as a result of the combination of both solutions the best of both solutions was used to yield more accurate data. LiDAR acquisition was limited to periods when the PDOP was less than 3.2.

The GPS trajectory was combined with the raw IMU data and post-processed using Applanix Inc.'s POSPROC (version 4.3) Kalman Filtering software. This results in a two-fold improvement in the attitude accuracies over the real-time INS data. The best estimated trajectory (BET) and refined attitude data are then re-introduced into the LEICA ALS post processor or REALM Survey Suite OPTECH to compute the laser point-positions. The trajectory is then combined with the attitude data and laser range measurements to produce the 3-dimensional coordinates of the mass points.

All return values are produced within ALS Post Processing software or REALM Survey Suite OPTECH software. The multi-return information minus the last return provides a useful depiction of the "canopy" within the project area. The last return is further processed to obtain the "Bare Earth Dataset" as a deliverable. All LiDAR data is processed using the binary LAS format 1.0 file format.

LiDAR filtering was accomplished using TerraSolid, TerraScan LiDAR processing and modeling software. The filtering process reclassifies all the data into classes with in the LAS formatted file based scheme set using the LAS format 1.0 specifications or by the client. Once the data is classified, the entire data set is reviewed and manually edited for anomalies that are outside the required guidelines of the product specification or contract guidelines, whichever apply. Table 4 indicates the required product specifications.

Table 4: Processing Accuracies and Requirements

Accuracy of LiDAR Data (H)	1 meter RMSE
Accuracy of LiDAR data in bare areas	18.5 cm RMSE
Accuracy of LiDAR data in vegetated areas	37 cm RMSE
Percent of artifacts removed (terrain and vegetation dependent)	90%
Percent of all outliers removed	95%
Percent of all vegetation removed	95%
Percent of all buildings removed	98%

The coordinate and datum transformations were then applied to the data set to reflect the required deliverable projection, coordinate and datum systems as provided in the contract. The final data is in State Plane Washington North Coordinate System with the horizontal and vertical units being in feet.

On some tiles, there were more second returns than first returns because with the system, the first return is the last return if only the first return is received. What this means is that if the electronics receive only one return it is the first return, but becomes the last return because it assumes it is the farthest thing hit, most likely the ground. Therefore, it becomes the last (second) return. This then heightens the possibility to better define the ground.

The client required deliverables were then generated. These included bare earth ASCII files in the form of comma delimited XYZIR, where “I” is intensity and “R” is return value. These files were created from the LAS files.

5 GROUND CONTROL AND ACCURACY ASSESSMENT

5.1 Network Scope

During the LiDAR campaign, the Sanborn field crew conducted a GPS field survey using Novatel DL4-Plus Survey Grade GPS receivers to establish final coordinates of the ground base stations for final processing of the base-remote GPS solutions. NGS points numbered 701 (PID: TR2747), 702 (PID: TQ0548), 901 (PID: TR0036), 902 (PID: TR0222), 903 (PID: TR0023) and one new point 501 set at Skagit Regional Airport were used for the LiDAR missions. The new 501 is located in the grassy area halfway up the abandoned taxi way. Each station was occupied for at least 45 minutes in order to obtain the best possible solution during baseline processing in the event that the baselines where not occupied during collection. In most cases the baselines between two points during collection where occupied between 2 and 8 hours depending on collection window. See Table 5 for station names, orders and constraints.

Table 5: NGS Control Constraints

Horizontal

Code	NGS Station Name	PID	Order	Constrain
901	V 454	TR0036	1st	Checkpoint
902	POT TXY 3	TR0222	B	Constrained
903	K 61	TR0023	A	Constrained
701	Bay View CBL 1140	TR2747	B	Checkpoint
702	GP 37020 9	TQ0548	A	Constrained

Vertical

Code	NGS Station Name	PID	Order	Constrain
901	V 454	TR0036	1 – I	Constrained
902	POT TXY 3	TR0222	1 – I	Constrained
903	K 61	TR0023	1 – I	Constrained

5.2 Data Processing and Network Adjustment

The static baselines created between points 501, 701, 702, 901, 902 and 903 were processed using Trimble Geomatics Office™ (Ver. 1.62) software. Fixed bias solution was obtained for the baselines. The broadcast ephemeris was used, since the accuracy and extent of the network does not warrant the use of the precise ephemeris. The results were satisfactory; therefore, fulfilling project specifications for first order control network. See Table 6 for loop closure summary.

Table 6: Survey Loop Closure Summary

Loop	Δ Horiz (cm)	Δ Vert (cm)	Dist. (ft)	ppm
501-701-702-902-901-903	0.50	-0.20	242883	0.257

5.3 Final LiDAR Verification

The LiDAR data was evaluated using a collection of 60 GPS surveyed checkpoints. Although 60 points where collected, the resulting LiDAR terrain in areas of 15 points proved unaccepted for proper statistical analysis in these areas resulting in the dismissal of these points. 20 points were collected in each bare earth, low grass, and urban vegetation classes, see Figure 6 for diagram of the locations of the checkpoints. The LiDAR data was compared to each of these classes and Tables 7 through 10 indicate the results for each point and the overall results as it compares to the LiDAR data set.

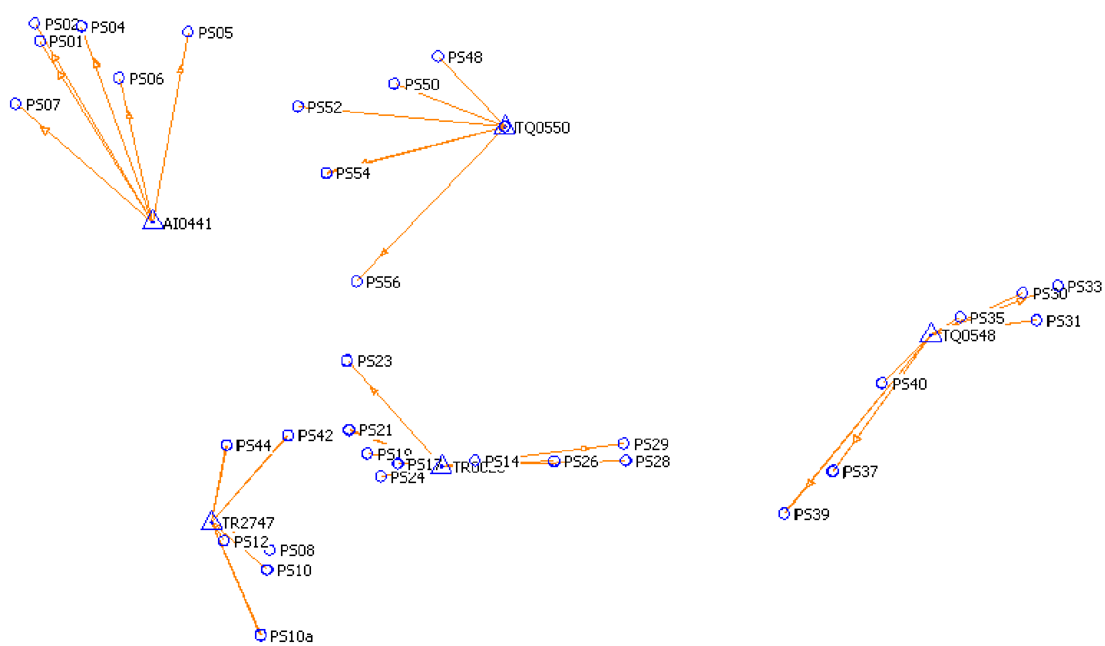

Figure 6: Survey Checkpoint Diagram

Table 7: Block 1 Checkpoint Results
(Elevations are in Feet)

Number	Easting	Northing	Known Z	Laser Z	Dz
6	1201880.778	732165.224	448.267	448.830	+0.563
2	1176038.808	701444.678	10.983	11.480	+0.497
4	1185522.554	726134.174	40.831	41.220	+0.389
7	1243771.006	729886.075	130.342	130.700	+0.358
5	1183544.370	732967.289	70.945	71.250	+0.305
8	1216632.565	711721.539	75.103	75.310	+0.207
1	1201899.338	731868.691	439.221	439.140	-0.081
53	1341756.983	720283.493	820.833	820.640	-0.193
60	1341753.971	720171.419	819.600	819.180	-0.420
61	1324578.231	709638.355	477.341	476.750	-0.591
54	1324592.355	709609.361	475.804	475.100	-0.704
62	1286695.579	700697.045	96.943	96.180	-0.763
55	1286693.522	700617.040	97.887	96.960	-0.927

Average dz	-0.105
Minimum dz	-0.927
Maximum dz	+0.563
Average magnitude	0.461
Root mean square	0.518
95% confidence	1.015
Std deviation	0.528

Table 8: Block 2 Checkpoint Results

Number	Easting	Northing	Known Z	Laser Z	Dz
3	1229819.874	655085.001	164.304	165.070	+0.766

Average dz	-0.766
Minimum dz	-0.766
Maximum dz	-0.766
Average magnitude	0.766

Root mean square 0.766
95% confidence 1.501
Std deviation 0.000

Given that there was one valid check point in this block, the statistical analysis of this block was not sufficient to valid the accuracy of the data set. But given the statistics of all the other blocks and the uniformity of the data set, it would be indicative that this block would fall within specification for the project.

Table 9: Block 3 Checkpoint Results

Number	Easting	Northing	Known Z	Laser Z	Dz
30	1306866.936	573731.593	383.322	383.860	+0.538
29	1313918.067	564417.917	350.788	351.320	+0.532
21	1306859.342	573464.003	381.423	381.780	+0.357
28	1326060.583	560219.558	97.823	98.120	+0.297
18	1356264.518	561595.185	127.041	127.310	+0.269
20	1314029.610	564451.931	355.598	355.720	+0.122
23	1319264.298	555229.165	69.704	69.420	-0.284
16	1257635.194	530247.614	17.256	16.780	-0.476
13	1257742.490	530247.113	17.278	16.730	-0.548
15	1274541.359	518593.631	21.497	20.860	-0.637
14	1272188.308	493155.666	11.550	10.890	-0.660
17	1343316.175	559234.020	90.501	89.830	-0.671
11	1272276.925	493021.819	9.834	9.060	-0.774
10	1275689.895	526416.772	29.129	28.330	-0.799

Average dz -0.195
Minimum dz -0.799
Maximum dz +0.538
Average magnitude 0.497
Root mean square 0.535
95% confidence 1.048
Std deviation 0.517

Table 10: Block 4 Checkpoint Results

Number	Easting	Northing	Known Z	Laser Z	Dz
23	1319264.298	555229.165	69.704	69.940	+0.236
24	1387280.585	561266.400	202.654	202.910	+0.256
25	1415365.655	561665.178	194.354	194.360	+0.006
26	1414590.786	568240.904	1080.900	1079.570	-1.330
32	1387326.028	561279.126	202.524	202.900	+0.376
33	1415308.146	561682.943	191.751	190.650	-1.101
34	1535212.986	610839.148	490.414	490.360	-0.054

35	1571097.865	627452.980	1224.399	1224.980	+0.581
36	1576619.561	616646.189	1229.710	1229.530	-0.180
37	1546569.087	617883.046	846.264	846.700	+0.436
39	1477616.213	540650.116	317.526	317.960	+0.434
40	1515962.292	592070.523	416.997	417.700	+0.703
41	1576556.318	616726.736	1228.988	1229.890	+0.902
42	1585006.361	630207.995	2122.560	2122.360	-0.200
43	1546610.793	617846.440	848.582	848.140	-0.442
45	1477556.952	540571.292	317.597	317.490	-0.107
46	1515910.106	591997.430	417.152	417.580	+0.428

Average dz	+0.056
Minimum dz	-1.330
Maximum dz	+0.902
Average magnitude	0.457
Root mean square	0.581
95% confidence	1.138
Std deviation	0.596

6 FINAL DATA

6.1 Spatial Reference Framework

The horizontal datum associated with the LiDAR data is NAD83 (1993), as realized by the physical NGS control monuments used to constrain the survey control network. The vertical datum associated with the LiDAR data is the NAVD88, as realized by the physical NGS benchmarks used to constrain the survey control network. The data is in State Plane Washington North Coordinate System. All units are in feet. The referenced Geoid model is Geoid03

6.2 File Structure

The final data was in four deliverable blocks. Block one contains files PS0001 through PS1250. Block two contains files PS1251 through PS2735. Block three contains files in the southwestern project area. Block four contains files in the eastern project area. Included in each block are both the LAS files and the bare earth files in the format of XYZIR (where “I” is intensity value and “R” is return value.)

6.3 Equipment

The IMU used in the Leica LiDAR system is a Litton LN200 510 IMU and the IMU for the Optech system is a AIMU 410. The POS electronic for the LEICA is a POS/AV 510 and the OPTECH is A POS/AV 410. The systems report attitude at 200hz or two hundred times per second. GPS CARDS for both Systems are Novatel. The GPS receivers for the base stations are Novatel DL-4 plus survey grade GPS receivers and the Antennas are Novatel 703 L1/L2 antennas. The aircraft antennas for both aircraft are Sensor system L1/L2 26db antennas provided by Applanix. These ground base receivers collect data at .5 second epochs.