SANBORN Total Geospatial Solutions

State of Minnesota LiDAR Project/USGS Cooperative Agreement

Minnesota River Basin
LiDAR Acquisition – South Dakota

2011

The Minnesota Department of Natural Resources contracted with Sanborn to provide LiDAR mapping services for eastern South Dakota. Utilizing multi-return systems, Light Detection and Ranging (LiDAR) data in the form of 3-dimensional positions of a dense set of mass points was collected for approximately 1,946 square miles. All systems consist of geodetic GPS positioning, orientation derived from high-end inertial sensors and high-accurate lasers. The sensor is attached to the aircraft's underside and emits rapid pulses of light that are used to determine distances between the plane and terrain below.

Specifically, the Leica ALS-50 LiDAR system was used to collect data for the 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.

Eight airborne GPS (Global Positioning System) base stations were used in the South Dakota project. An existing point was used at the Watertown Municipal Airport, NGS point with PID: PR1202. The other base stations were set up at National Geodetic Survey (NGS) markers. NGS points with PID: PR1098 located in Watertown, PID: QQ0759 located North East of Sisseton, PID: AE9746 and PID: AE9745 located in East Milbank, and PID: QQ0680 located north of Sisseton. Two set points surveyed in by Sanborn were also used. These seven base stations were tied to the other point 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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1.0 INTRODUCTION

This document contains the technical write-up of the LiDAR campaign, including system calibration techniques, the establishment and processing 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

As stated in the statement of work for acquisition and production of the standard data for South Dakota. This LiDAR operation was designed to create a data sets that will establish an authoritative source for elevation information for eastern South Dakota.

1.3 Project Location
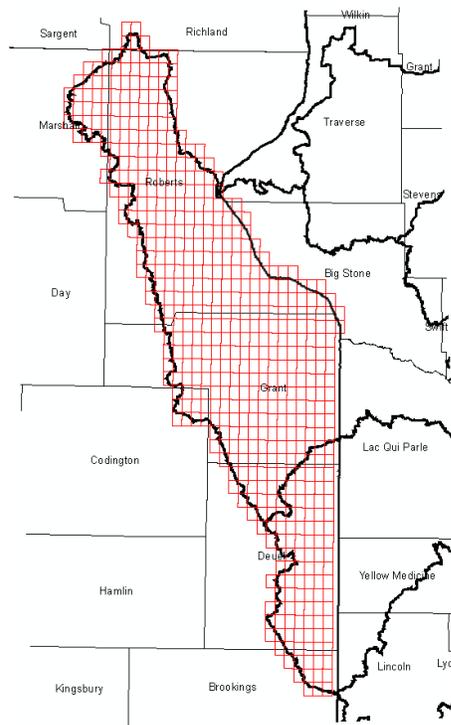
Figure 1: Area of Collection

1.4   Standard Specifications for LiDAR

Project Specifications					
Area (sq. mi)	1,946	**Product type**	Standard	**Projection**	UTM Zone 14 NAD83, Meters NAVD88, Meters
Vertical Accuracy (CM)	Bare Earth 18cm	**Check Points required**	Yes	**Horizontal Datum Vertical Datum**	NAD83 NAVD88
Horizontal accuracy (M)	1 Meter	**Number Collected**	62	**Units**	Meters

2.0 LIDAR 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 system. 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 the plane and the ALS-50 system configurations.

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 is 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 system 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.
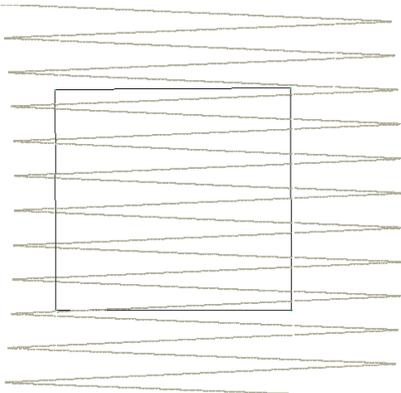
Figure 2: Calibration Pass 1
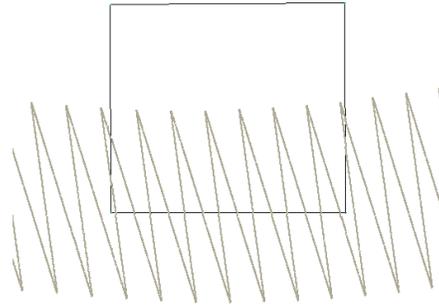
Figure 3: Calibration Pass 2

2.4   Runway Calibration, System Performance Validation

A runway was precisely-surveyed at the Watertown Municipal Airport for South Dakota 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. A Triangulated Irregular Network (TIN) surface is created from these passes. The ground control x,y,z points are then compared with the z of the LiDAR surface to compute vertical residuals of the LiDAR data. After careful analysis of noise associated with non-runway returns, any system bias is documented and removed from the process.

Figure 4: Runway Calibration

3.0 RUNWAY CALIBRATION AND SYSTEM PERFORMANCE VALIDATION

3.1 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 RMSE 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.

The calibration is done based on a kinematic survey on the runway. Given that the Kinematic survey RMSE is no better than 4 centimeters as a result of none exact height of the antenna and weight of the aircraft. Sanborn was required to do additional check points in the project area to meet the 18 centimeter vertical accuracy requirement knowing that the calibration site is only good to 4 centimeters RMSE. A z bump adjustment was made to the entire data set based on the survey points in the project area and the relative accuracy of the data to itself and in all areas.
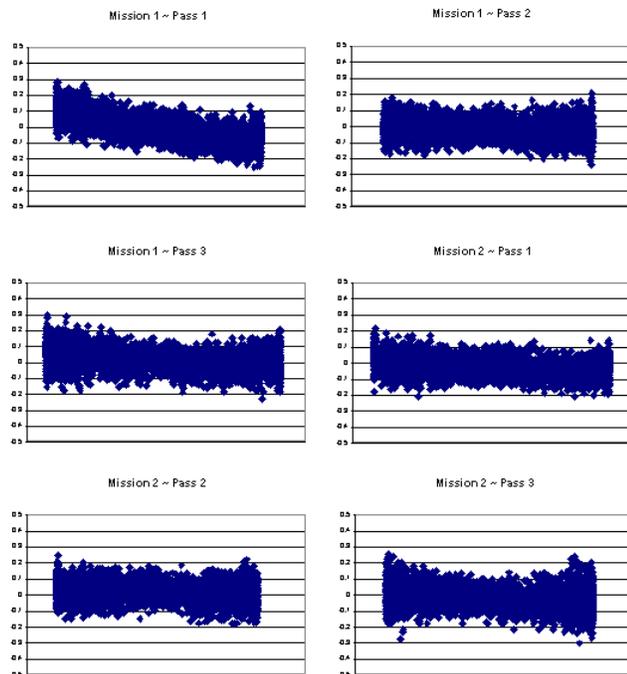
Figure 5: Runway Calibration Results

3.2 Daily Runway Performance/Data Validation Tests

Performance flights over the runway test field were performed before and after each mission. Table 1 shows the standard deviation and RMSE values of the residuals between the test flights and the known surface of the test ranges for each pass. The maximum RMSE value is 0.104 meters and the maximum standard deviation is 0.104 meters. The average RMSE among all test flights is 0.064 meters.

Table 1: Runway Validation Results for Watertown, South Dakota (Meters)

Mission	Passes	Standard Deviation	RMSE
Day306a	4	0.081	0.081
Day308b	4	0.065	0.065
Day308c	4	0.048	0.048
Day309a	4	0.056	0.056
Day309b	4	0.054	0.054
Day310a	4	0.064	0.064
Day310b	4	0.104	0.104
Day311a	4	0.079	0.079
Day311b	4	0.053	0.053
Day311c	4	0.054	0.051
Day312a	4	0.051	0.050

4.0   LIDAR FLIGHT AND SYSTEM REPORT

4.1   Introduction

This section addresses LiDAR system, flight reporting and data acquisition methodology used during the collection of the South Dakota 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 set up on PR1202 and the secondary GPS receivers placed at survey control points PR1098, QQ0759, AE9746, AE9745, QQ0680, and 2 points set by Sanborn which are within the project area or within the required baseline specifications of the project.

Pre-flight checks such as cleaning the sensor head glass are performed. A four 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 ten 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 with a flying height of 2,676 meters above ground level (AGL) for the Leica ALS-50 on a mission to mission basis.

Table 2: LiDAR Leica Acquisition Parameters

Average Altitude	2,676 Meters AGL
Airspeed	~130 Knots
Scan Frequency	34.3 Hertz
Scan Width Half Angle	17 Degrees
Pulse Rate	89,200 Hertz

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. Any problematic data could then be re-flown immediately as required. Final data processing was completed in the Colorado Springs office.

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

Mission	Date	Start Time	End Time	Altitude (m)	Airspeed (Knots)	FOV	Scan Rate	Pulse Rate	PDOP
306a	Nov 02	02:15	08:16	2676	130	34°	34.3	89200	1.71
308b	Nov 04	05:30	09:20	2676	130	34°	34.3	89200	1.85
308c	Nov 04	09:40	12:45	2676	130	34°	34.3	89200	2.02
309a	Nov 05	12:00	4:55	2676	130	34°	34.3	89200	1.65
309b	Nov 05	05:30	10:50	2676	130	34°	34.3	89200	1.90
310a	Nov 06	01:40	6:00	2676	130	34°	34.3	89200	1.70
310b	Nov 06	06:40	10:45	2676	130	34°	34.3	89200	1.92
311a	Nov 07	01:50	07:05	2676	130	34°	34.3	89200	1.80
311b	Nov 07	07:40	01:25	2676	130	34°	34.3	89200	1.96
311c	Nov 07	08:20	01:00	2676	130	34°	34.3	89200	1.67
312c	Nov 08	06:10	08:20	2676	130	34°	34.3	89200	1.70

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™ 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 for the Leica system 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 for the Leica system. The multi-return information is processed to obtain the "Bare Earth Dataset" as a deliverable. All LiDAR data is processed using the binary LAS format 1.2 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 1.2 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.

The coordinate and datum transformations are then applied to the data set to reflect the required deliverable projection, coordinate and datum systems as provided in the contract.

The client required deliverables are then generated. At this time, a final QC process is undertaken to validate all deliverables for the project. Prior to release of data for delivery, Sanborn's quality control/quality assurance department reviews the data and then releases it for delivery.

Table 4: Processing Accuracies and Requirements

Accuracy of LiDAR Data (H)	1 m RMSE
Accuracy of LiDAR data in bare areas	18 cm RMSE
Accuracy of LiDAR data in vegetated areas	30 cm RMSE
Percent of artifacts removed (terrain and vegetation dependent)	95%
Percent of all outliers removed	98%
Percent of all vegetation removed	97%
Percent of all buildings removed	99%

5.0   GEODETIC BASE NETWORK

5.1   Network Scope

During the LiDAR campaign, the Sanborn field crew conducted a GPS field survey to establish final coordinates of the ground base stations for final processing of the base-remote GPS solutions. NGS points PR1098, QQ0759, AE9746, AE9745, PR1202, QQ0680, and 2 points set by Sanborn were used for the LiDAR missions. See table 5 for station names, orders and constraints.

5.2   Data Processing and Network Adjustment

The static baselines created between points PR1098, QQ0759, AE9746, AE9745, PR1202, QQ0680, and the 2 points set by Sanborn were processed using Trimble Geomatics Office^{TM} (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.
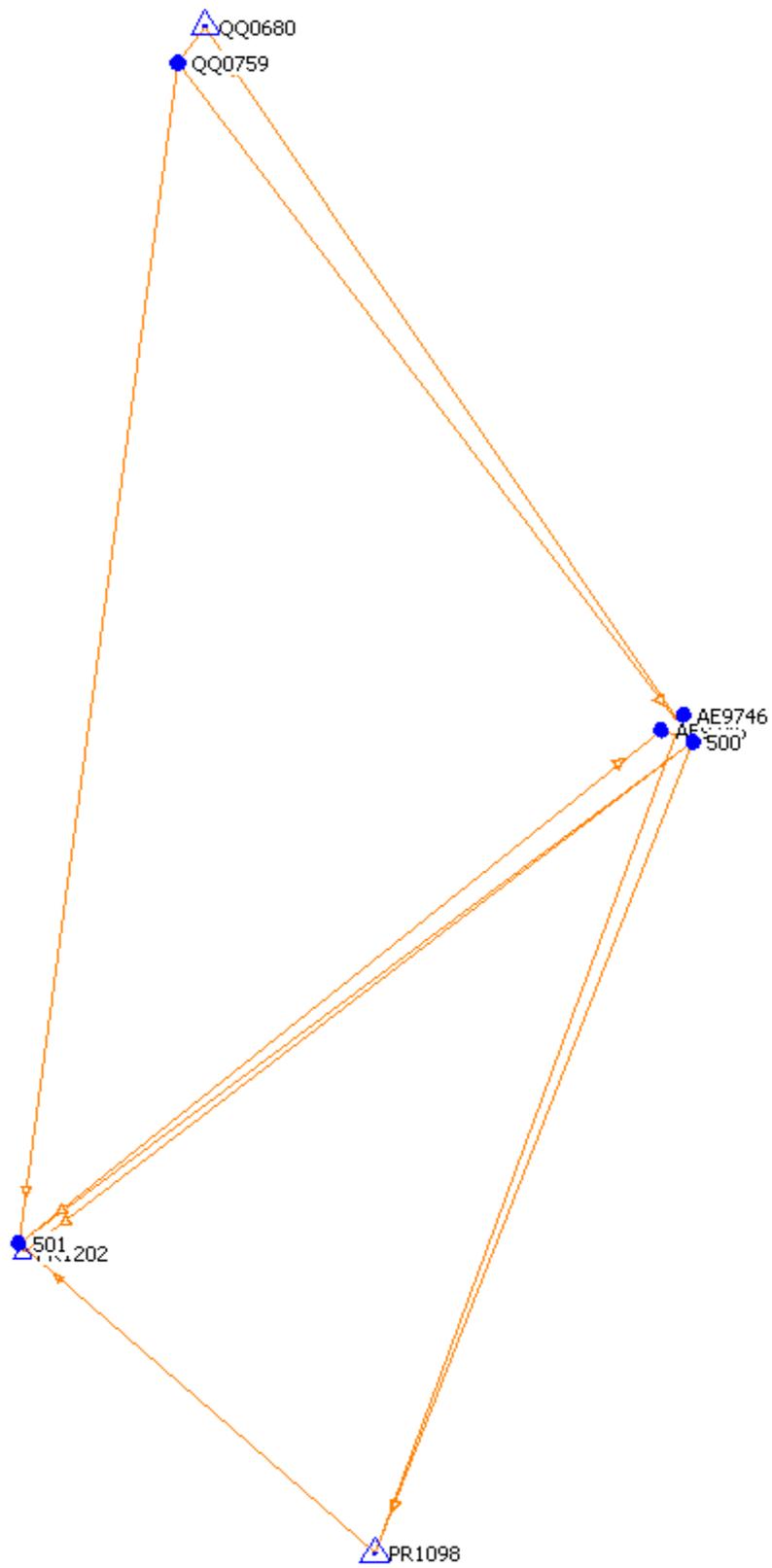
Figure 6: Survey Network Diagram

Table 5: NGS Control Constraints
Horizontal

Code	NGS Station Name	PID	Constrain
PR1098	I29 162.17	PR1098	Constrained
QQ0759	SISSPORT	QQ0759	NGS Check
PR1202	ARP	PR1202	Constrained
QQ0680	I29 234.3	QQ0680	Constrained
500	None	None	Sanborn Set
501	None	None	Sanborn Set

Vertical

Code	NGS Station Name	PID	Constrain
PR1098	I29 162.17	PR1098	Constrained
AE9746	12 393.30	AE9746	NGS Check
AE9745	12 392.92	AE9745	NGS Check
QQ0680	I29 234.3	QQ0680	Constrained
500	None	None	Sanborn Set
501	None	None	Sanborn Set

5.3   Final LiDAR Verification

The LiDAR data was evaluated using a collection of 62 GPS surveyed checkpoints. See figure 7 for diagram. For South Dakota, the root mean squared is 0.090 meters. The LiDAR data was compared to each of these classes yielding much better result than was required for the project. Table 6 indicates the results for South Dakota and each point including the overall results as it compares to the LiDAR data set.
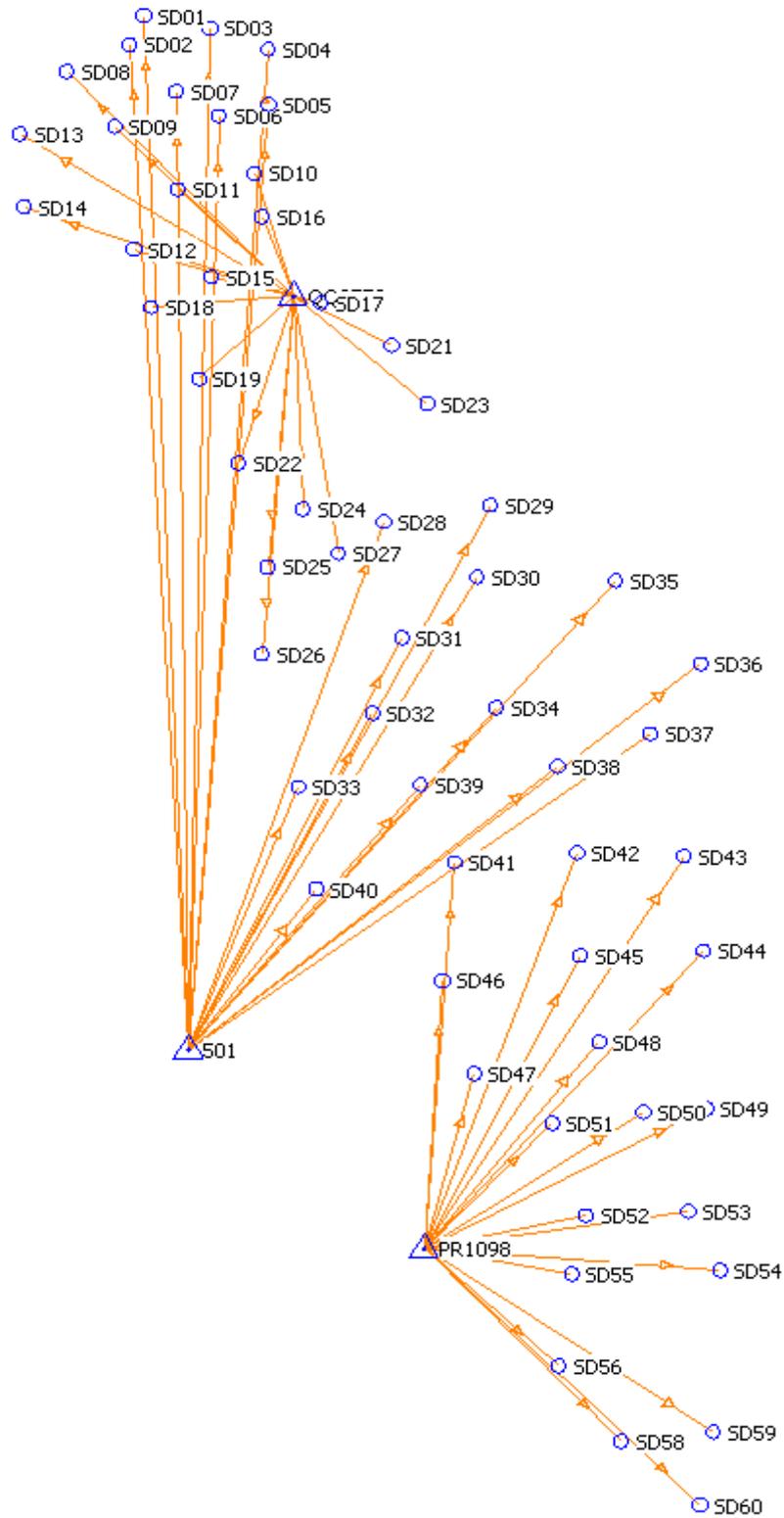
Figure 7: South Dakota Survey Checkpoint Diagram

Table 6: LiDAR Accuracy Assessment based on the Checkpoint Survey (Meters)

Name	Control X	Control Z	Control Z	Surface Z	Z Error
QQ0759	656253.314	5059054.337	353.344	353.432	-0.088
SD01	640609.863	5090098.448	367.271	367.253	0.018
SD02	639177.252	5086850.593	362.887	362.839	0.048
SD03	647541.016	5088683.513	364.754	364.908	-0.154
SD04	653607.262	5086390.297	365.299	365.346	-0.047
SD05	653633.581	5080298.604	372.927	373.008	-0.081
SD06	648488.524	5078964.778	362.955	362.991	-0.036
SD07	644022.077	5081755.286	364.016	364.019	-0.003
SD08	632621.764	5083905.926	379.872	379.882	-0.010
SD09	637615.887	5077855.440	379.675	379.738	-0.063
SD10	652184.507	5072631.844	363.251	363.241	0.010
SD11	644209.640	5070841.381	369.611	369.721	-0.110
SD12	639627.717	5064295.847	579.378	579.308	0.070
SD13	627746.566	5077017.061	546.624	546.644	-0.020
SD14	628189.749	5068969.992	579.949	580.047	-0.098
SD15	647717.104	5061231.385	399.457	399.586	-0.129
SD16	652951.663	5067834.290	352.763	352.695	0.068
SD17	659087.865	5058250.353	347.500	347.520	-0.020
SD18	641397.981	5057831.107	612.698	612.800	-0.102
SD19	646374.301	5049900.965	603.379	603.371	0.008
SD21	666417.202	5053583.521	334.792	334.760	0.032
SD22	650487.335	5040609.860	561.031	561.013	0.018
SD23	670123.829	5047227.571	334.605	334.506	0.099
SD24	657205.350	5035559.816	420.486	420.520	-0.034
SD25	653552.950	5029158.631	561.218	561.272	-0.054
SD26	652939.912	5019569.770	613.043	613.078	-0.035
SD27	660897.206	5030620.382	407.397	407.471	-0.074
SD28	665606.200	5034192.342	356.915	356.912	0.003
SD29	676726.471	5036023.160	324.938	325.009	-0.071
SD30	675329.961	5028057.272	352.553	352.544	0.009
SD31	667540.076	5021293.405	389.049	389.078	-0.029
SD32	664497.099	5012958.359	494.475	494.588	-0.113
SD33	656728.306	5004814.797	620.023	620.036	-0.013
SD34	677334.923	5013638.194	360.370	360.374	-0.004
SD35	689763.299	5027645.883	318.619	318.951	-0.332
SD36	698593.575	5018425.437	321.918	322.240	-0.322
SD37	693372.425	5010686.702	328.899	329.010	-0.111
SD38	683707.312	5007129.749	356.295	356.309	-0.014
SD39	669453.227	5005094.507	491.405	491.421	-0.016

SD40	658570.325	4993597.169	591.177	591.088	0.089
SD41	672953.977	4996467.290	504.986	505.072	-0.086
SD42	685715.029	4997516.267	365.195	365.187	0.008
SD43	696877.628	4997235.144	345.354	345.274	0.080
SD44	698877.798	4986730.386	348.717	348.658	0.059
SD45	686068.653	4986267.726	434.137	434.101	0.036
SD46	671725.020	4983455.106	574.164	574.116	0.048
SD47	675047.644	4973162.713	573.632	573.728	-0.096
SD48	687993.081	4976728.592	506.363	506.324	0.039
SD49	699211.638	4969357.451	423.812	423.844	-0.032
SD50	692649.806	4968971.262	499.206	499.250	-0.044
SD51	683143.922	4967742.728	555.161	555.194	-0.033
SD52	686666.464	4957468.899	542.967	543.089	-0.122
SD53	697317.130	4957903.388	499.141	499.184	-0.043
SD54	700640.609	4951507.662	522.651	522.618	0.033
SD55	685201.658	4951001.735	560.430	560.543	-0.113
SD56	683836.410	4940915.323	602.502	602.564	-0.062
SD58	690302.659	4932541.725	599.443	599.551	-0.108
SD59	699912.954	4933518.881	545.779	545.879	-0.100
SD60	698537.969	4925547.067	537.590	537.677	-0.087

Average dz	-0.040
Minimum dz	-0.332
Maximum dz	0.099
Root Mean Square	0.090

6.0   COORDINATES AND DATUM

6.1   Introduction

The final adjustment was constrained to the published NAD83 geodetic coordinates (ϕ, λ) and NAVD88 elevations. The adjustment was cross-referenced to the GEOID03 model to enable the estimation of orthometric heights.

6.2   Horizontal Datum

The final horizontal coordinates are provided in UTM on the North American Datum of 1983 in units of meters.

6.3   Vertical Datum

The final orthometric elevations were determined for all points in the network using Geoid03 model and are provided on the North American Vertical Datum of 1988 in units of meters.