Alliance for Sustainable Energy, LLC

LiDAR Campaign (Boston) Report of Survey

2010

EXECUTIVE SUMMARY

The Alliance for Sustainable Energy, LLC contracted with Sanborn to provide LiDAR mapping services for the Boston area. 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 90 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.

Four airborne GPS (Global Positioning System) base stations were used in the Boston, Massachusetts project. An existing point was used at the Plymouth Municipal Airport, NGS point with PID: AI5610. The other base stations were set up at National Geodetic Survey (NGS) markers. NGS point with PID: MY0588 located at Charlestown at the Boston Navy ship yard, PID: AJ4040 located in Weymouth and PID: AJ4042 located in Avon. These three 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 FEMA data for Boston. This LiDAR operation was designed to create a data sets that will establish an authoritative source for elevation information for the city of Boston.

1.3 Project Location

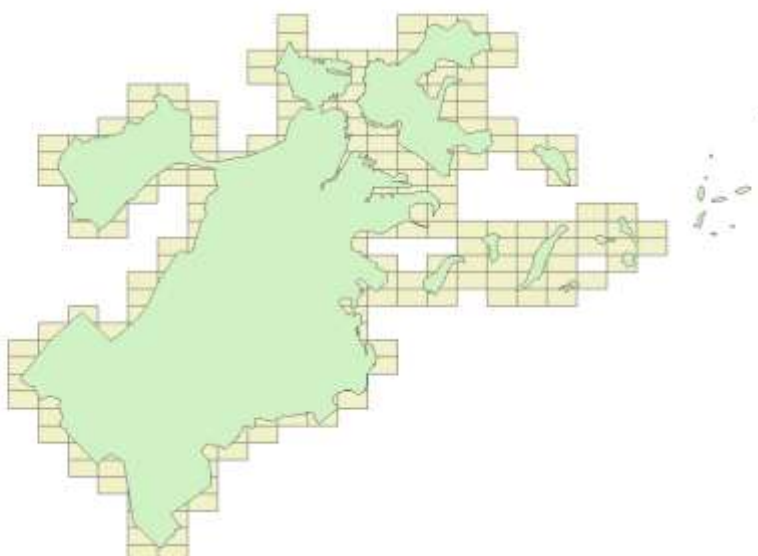

Figure 1: Area of Collection

1.4 Standard Specifications for LiDAR

Project Specifications					
Area (sq. mi)	90	**Product type**	Fema	**Projection**	Massachusetts Mainland FISP 2001 State Plane
Vertical Accuracy (CM)	Bare Earth 15	**Check Points required**	Yes	**Horizontal Datum Vertical Datum**	NAD 83/NAVD 88
Horizontal accuracy (M)	1meter	**Number Collected**	20	**Units**	US Feet

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.

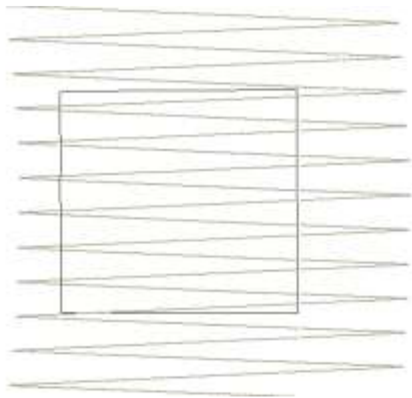

Figure 2: Calibration Pass 1

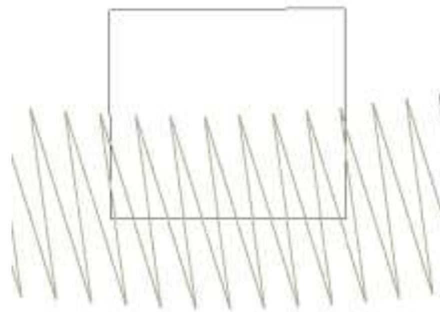

Figure 3: Calibration Pass 2

2.4 Runway Calibration, System Performance Validation

An active asphalt runway was precisely-surveyed at the Plymouth Municipal Airport for Boston, Massachusetts 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.

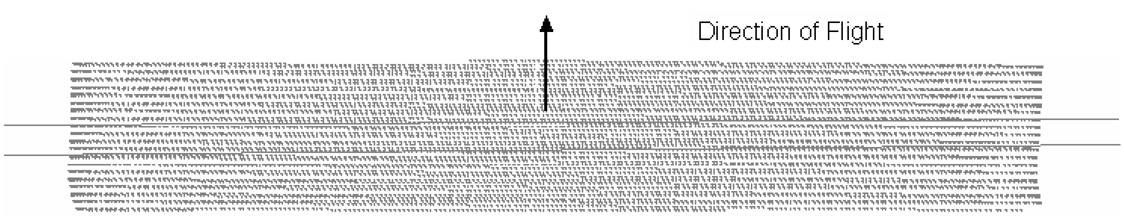

Figure 4: Runway Calibration

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 15 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.

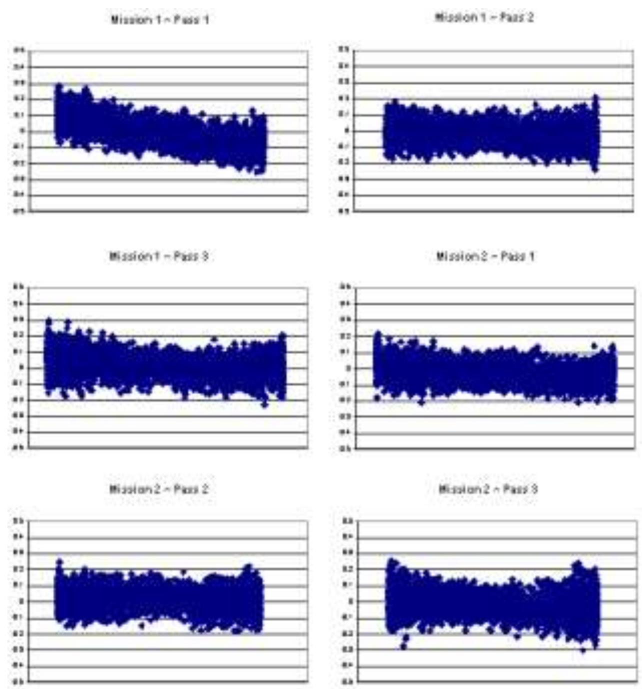

Figure 5: Runway Calibration Results

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 0.053 meters and the maximum standard deviation is 0.0492 meters. The average RMSE among all test flights is 0.05125 meters.

Table 1: Runway Validation Results for Boston, Massachusetts (Meters)

Mission	Passes	Standard Deviation	RMSE
Day314a	4	0.0492	0.0530
Day315a	4	0.0407	0.0495

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 Boston, Massachusetts 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 AI5610 and the secondary GPS receivers placed at survey control points MY0588, AJ4040 and AJ4042 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 1500 meters above ground level (AGL) for the Leica ALS-50 on a mission to mission basis.

Table 2: LiDAR Leica Acquisition Parameters

Average Altitude	1500 Meters AGL
Airspeed	~120 Knots
Scan Frequency	46 Hertz
Scan Width Half Angle	25 Degrees
Pulse Rate	74,400 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)	Scan Angle	Scan Rate	Pulse Rate	PDOP
314a	Nov 10	05:45	11:09	1500	120	50˚	46	74400	1.8
315a	Nov 11	04:58	08:50	1500	120	50˚	46	74400	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™ 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	15 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 MY0588, AJ4040, AI5610 and AJ4042 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 MY0588, AJ4040, AI5610 and AJ4042 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.

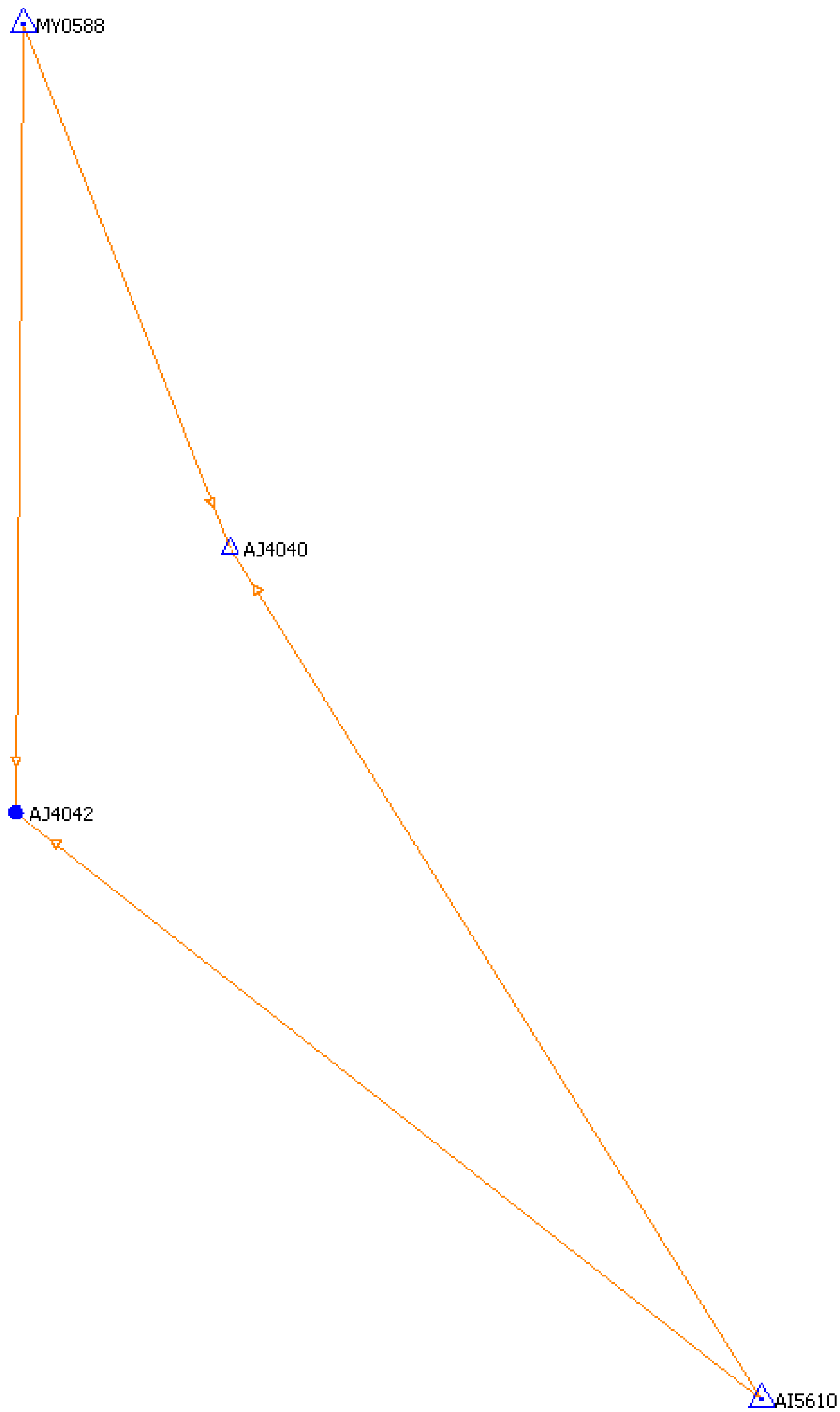

Figure 6: Survey Network Diagram

Table 5: NGS Control Constraints
Horizontal

Code	NGS Station Name	PID	Constrain
MY0588	TRI STA	MY0588	Constrained
AJ4040	438 G	AJ4040	Constrained
AI5610	PYM A	AI5610	Constrained
AJ4042	438 J	AJ4042	Checkpoint

Vertical

Code	NGS Station Name	PID	Constrain
MY0588	TRI STA	MY0588	Constrained
AJ4040	438 G	AJ4040	Checkpoint
AI5610	PYM A	AI5610	Constrained
AJ4042	438 J	AJ4042	Checkpoint

Table 6: Survey Loop Closure Summary

Loop	Δ Horiz (cm)	Δ Vert (cm)	Dist. (m)	ppm
MY0588:AJ4040:AI5610:AJ4042	0.6	-4.8	123974.266	0.389

5.3 Final LiDAR Verification

The LiDAR data was evaluated using a collection of 20 GPS surveyed checkpoints. See figure 6 for diagram. For Boston, Massachusetts the standard deviation is 0.207 feet and the root mean squared is 0.203 feet. The LiDAR data was compared to each of these classes yielding much better result than was required for the project. Table 7 indicates the results for Boston, Massachusetts and each point including the overall results as it compares to the LiDAR data set.

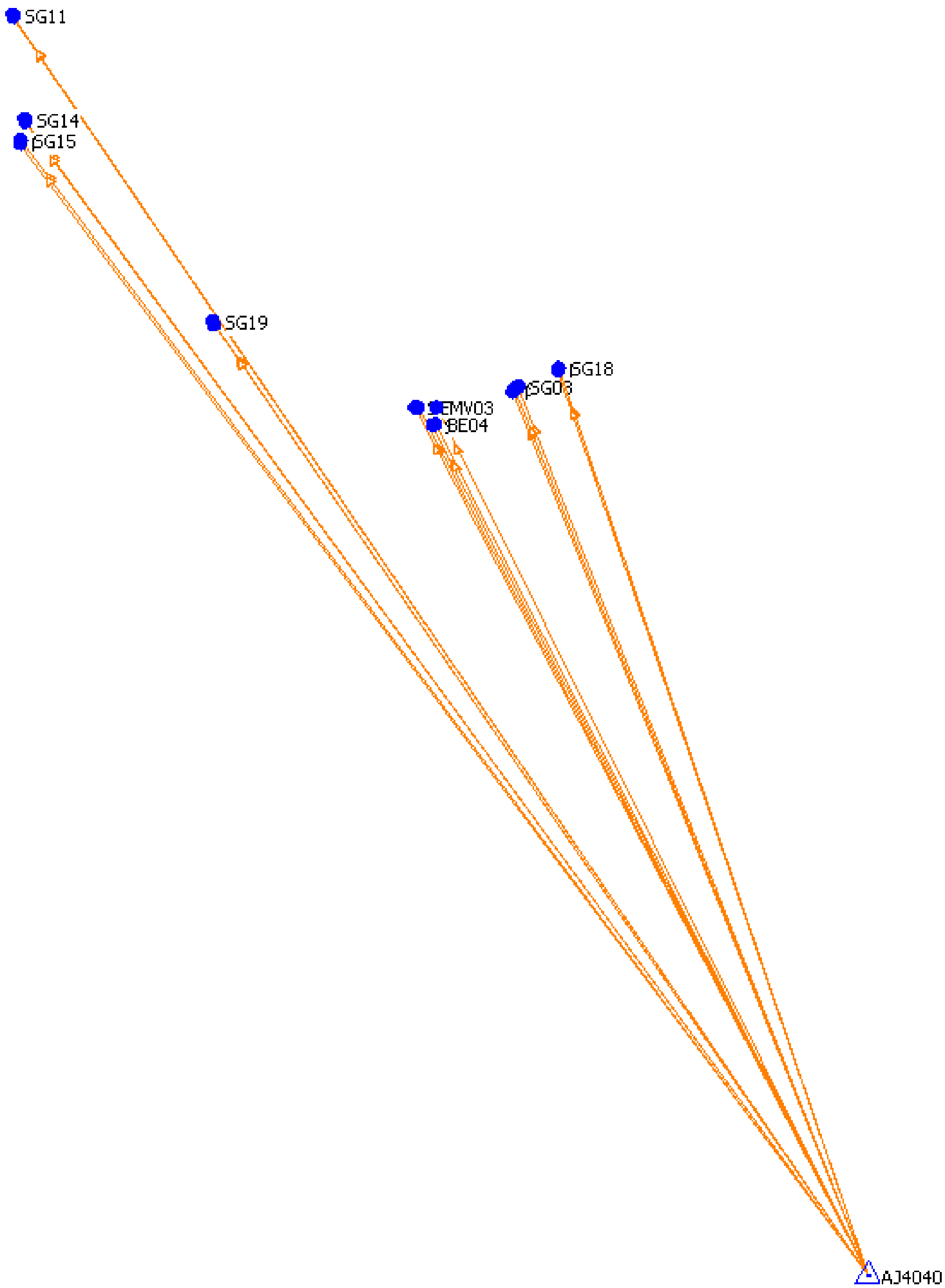

Figure 7: Boston Survey Checkpoint Diagram

Table 7: LiDAR Accuracy Assessment based on the Checkpoint Survey (US feet)

Name	Easting	Northing	Known Z	Laser Z	Dz
SG14	755883.54	2960473.569	3.473	3.81	0.337
MV03	778466.79	2944647.317	10.639	10.94	0.301
BE13	755905.472	2960335.729	3.557	3.8	0.243
SG06	782733.048	2945663.282	10.81	11.04	0.23
SG11	755222.823	2966211.956	11.427	11.64	0.213
SG15	755671.075	2959340.805	3.491	3.67	0.179
BE12	755240.608	2966088.694	12.362	12.54	0.178
SG20	766268.54	2949201.177	11.407	11.52	0.113
BE16	755634.569	2959145.001	4.087	4.19	0.103
SG19	766209.502	2949380.857	11.151	11.12	-0.031
BE07	782641.651	2945521.894	7.723	7.69	-0.033
BE04	778373.592	2943719.74	8.31	8.27	-0.04
SG05	778267.055	2943667.563	10.72	10.59	-0.13
SG18	785165.091	2946795.651	8.47	8.27	-0.2
SG08	782964.776	2945793.298	9.688	9.47	-0.218
BE17	785133.249	2946691.456	8.593	8.37	-0.223
BE02	777444.093	2944630.388	8.382	8.13	-0.252
SG01	777304.769	2944640.987	8.955	8.69	-0.265

Average dz	0.028
Minimum dz	-0.265
Maximum dz	0.337
Average magnitude	0.183
Root mean square	0.203
Std deviation	0.207

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 (NAD83 adjustment of 1992) 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.